DESIGN FOR RECYCLING

Under Extended Producer Responsibility

TEAM

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Understanding the Financial Implications of Automobile Design Choice under Extended Producer Responsibility by Considering the Cost of Removing Contaminants at the Dismantling Phase

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management

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SIGNATURE PAGE

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The mission of the Bren School of Environmental Science & Management is to produce professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. It is a three quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

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ABSTRACT

Automobiles are manufactured using a variety of materials, including hazardous substances. Extended Producer Responsibility (EPR) is an environmental policy principle that addresses this concern. Under EPR, automobile manufacturers assume responsibility for the life-cycle impacts of their vehicles. In Europe, the ELV Directive and EPR policy principles are changing business models of manufacturers and are potentially having an effect on the relationship between auto companies, dismantlers, recyclers, and consumers.

Our objective is to assist auto manufacturers in choosing between redesign of their product versus removal of contaminants at the vehicle end-of-life. We have collected data from industry and academic sources and created a model that estimates end-of-life removal costs for lead and mercury by considering disassembly and disposal costs for parts containing these materials in a generic passenger vehicle, the 2010 Toyota Camry.

The result of our analysis can be represented by a cost curve. By arranging the parts containing these hazardous materials in order of increasing average cost of contaminant removal, we are able to visualize the total cost of removing contaminants represented by the area under a cost curve. This allows manufacturers to identify the most cost-effective sequence of part removal and determine which parts the lead or mercury should be eliminated from in vehicle design. We show that the system-wide costs of imposing a design ban and disposal ban on lead exceed the costs of imposing an EPR program. The framework of our model can be used by policymakers to determine the most cost-effective policies for achieving lead and mercury reduction measures.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

We estimated the cost of removing Substances of Concern (SOCs) from automobiles at the end of their life. To do this, we created a model to calculate the total end of life removal costs that consist of dismantling and disposal costs. We then applied the model to lead and mercury in the 2010 Toyota Camry.

Automobiles contain many hazardous materials, including lead, mercury, arsenic, antimony, tin, cobalt, chromium, nickel, silver, and copper. When they enter the waste stream at the end of a vehicle's life, these contaminants have the potential to cause harm to human health and the environment.

One way to mitigate this harm is to remove contaminants at the end of life stage of the vehicle life cycle. An end of life vehicle (ELV) typically goes to a dismantler, which removes all parts and materials that can be sold at a profit and sends the remaining materials to a shredder, which recovers ferrous metals and non-ferrous metals before sending the remaining waste to the landfill. Both dismantlers and shredders have the opportunity to remove contaminants before they are discarded into the environment.

In the past, regulation of contaminants has been achieved through laws that prohibit actors from releasing contaminants into the environment. One example is the Resource Conservation and Recovery Act (RCRA). Such regulation puts the burden of removing contaminants on the end of life actors – the dismantlers and the shredders. It does not motivate manufacturers to change their designs. In order to encourage better designs, a new approach is needed.

One promising new approach has come to be called "extended producer responsibility" (EPR). EPR is a type of regulation that holds the manufacturer responsible for end of life outcomes. In practice, EPR requires manufacturers to either remove contaminants from their designs, or to pay for end of life treatment of their vehicles (Walls, 2006).

The European Union has pursued EPR aggressively with its End of Life Vehicles Directive (Konz, 2009). The ELV directive mandates that at least 95% of an automobile must be recyclable or reusable by January 2015 (Konz, 2009). It also targets specific hazardous materials, such as lead, mercury, and cadmium, either banning their use or making manufacturers responsible for their safe removal at the end of life (Konz, 2009). This approach has significantly changed the role manufacturers play in the end of life process.

By comparison, the United States has no national end of life vehicle policy (Konz, 2009). Individual states have taken steps to regulate manufacturers, but these scattered efforts fall short of a comprehensive EPR policy. Nevertheless, it is likely that the automobile recycling infrastructure in the US will eventually be required to comply with policies similar to the EU's End of Life Vehicle Directive (Kumar & Sutherland, 2008). Therefore, extended producer responsibility and its economic implications are a very real concern for the domestic auto industry.

Manufacturers faced with extended producer responsibility need to compare the cost of removing contaminants from their designs with the cost of removing those contaminants at the end of life. Unfortunately, there is very little information about these end of life costs. In order to make these costs more visible, we created a model of end of life costs which includes both disassembly and disposal costs at the dismantling phase of the life cycle.

We applied our model to lead and mercury in the 2010 Toyota Camry. As the best selling passenger car in North America, the Toyota Camry is reasonably representative of the US auto fleet (Cars.com, 2012).

We found that 141g of lead exists in parts which can feasibly be removed, but which are not currently removed from vehicles at

Figure 1: A model of contaminant removal costs

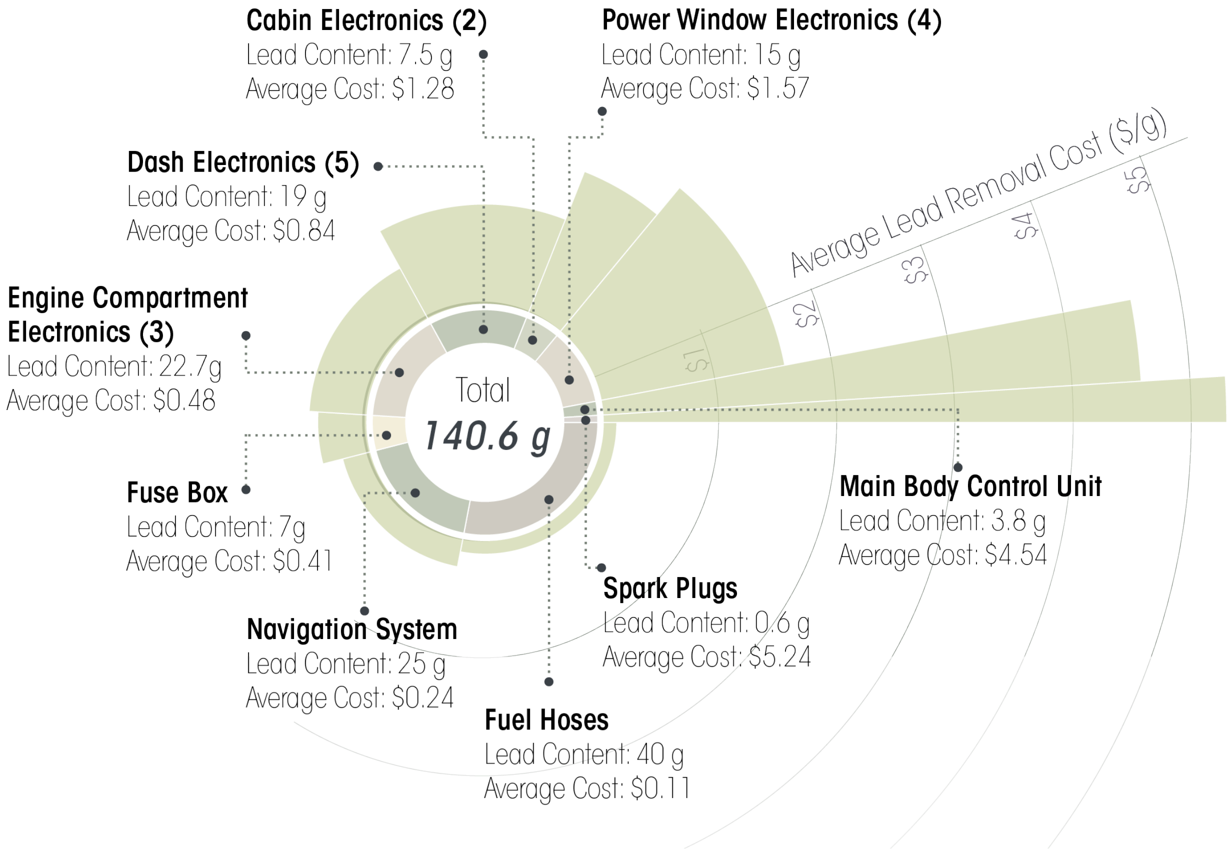
Our model uses the labor rate and part dismantling times to estimate the disassembly cost, the weight of the contaminated part to calculate disposal cost, and contaminant content data to determine the quantity of contaminants removed.

the end of their life. Most of this lead is contained in electronic control units, but lead also exists in fuel hoses, the fuse box, and spark plugs. The cost to remove and dispose of all the feasible lead-containing parts is $93.77.

$93.77

The cost to remove and dispose of all the feasible lead-containing parts.

Figure 2: The cost of removing lead



We also found that an additional 61mg of mercury can feasibly be removed. Removable mercury exists in the instrument panel, display screen, and headlamps. The cost to remove and dispose of these parts is $12.34 per vehicle.

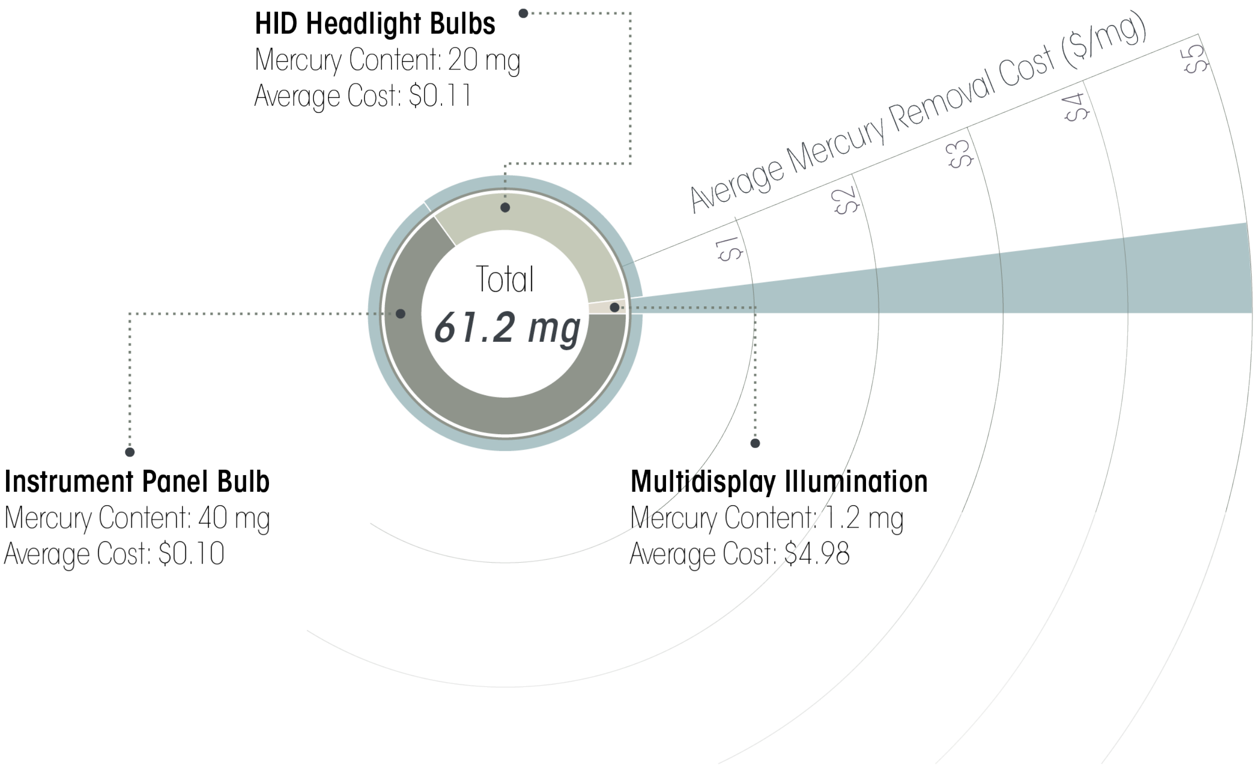
$12.34

The cost to remove and dispose of all the feasible mercury-containing parts.

Across the entire 2010 Camry fleet, this amounts to 46 metric tons of lead, which can be removed at a cost of $31M, and 20kg of mercury, which can be removed at a cost of $4M.

We believe these results can be used to guide the manufacturer decision process; they illustrate the threshold against which design costs should be measured. If costs associated with retooling and redesign are less than these ELV costs, then design changes are economically preferable.

Figure 3: The cost of removing mercury



PROJECT OBJECTIVES AND SIGNIFICANCE

> *The objective of this project is to understand the financial implications of automobile design choices under EPR policy by considering the cost of removing contaminants during the dismantling stage of the vehicle life cycle.*

Under extended producer responsibility, auto manufactures must either remove contaminants from their designs or pay to have those contaminants removed at the end of the vehicle's life. Therefore, every design choice has a consequence. The decision to use contaminants in the design carries a financial cost; the decision to remove contaminants from the design brings a financial benefit. Our objective is to explain and quantify these financial implications.

Under EPR, the financial consequences of design choices manifest during the end of life stage of the vehicle life cycle. The end of life stage consists of dismantling and shredding. In theory, contaminants could be removed at either of these stages. In practice, however, it is more efficient to remove them at the dismantling stage. Thus, our objective is to quantify the cost to remove contaminants at the dismantling stage.

This objective is significant for several reasons:

First, our project can help manufacturers to identify where in the life cycle it is most economical to remove contaminants. This life cycle management perspective is essential under extended producer responsibility, yet is currently lacking.

Second, our project can help dismantlers to determine the most cost-effective parts to remove at the dismantling stage. Environmental regulations are seldom absolute; they typically mandate the removal of a portion of the contaminants contained in a vehicle. By knowing the cost of removing those contaminants part-by-part, dismantlers can choose an optimal strategy.

Third, our project can help policymakers to understand the potential benefits of extended producer responsibility policies. If the cost to remove contaminants is low at the dismantling stage, there may be an opportunity for effective policy, regardless of the manufacturer's design cost to remove that same contaminant.

Furthermore, the project is made especially significant because of the increasing popularity of extended producer responsibility (EPR). The European Union has made a commitment to EPR with its End of Life Vehicles Directive. While not yet adopted in the United States and other nations, the End of Life Vehicles Directive offers a template for EPR which could easily spread worldwide.

In fact, there is evidence that the prospect of EPR already influences the decisions of American auto manufacturers. In 1997, Chrysler did an analysis which suggested that continued use of mercury switches would save the company $0.11 per switch. However, Chrysler estimated end of life costs at $0.23 per switch. Despite the fact that Chrysler does not bear end of life costs, it used this analysis to justify replacement of underhood mercury switches with rolling ball switches (Chrysler).

Given its significance, we expect the project to have value for several groups of stakeholders. Stakeholders of the recycling industry include the following: “government, automakers, suppliers, automobile consumers, automobile recyclers (dismantlers and shredders), secondary materials processors, and raw material suppliers” (Field III & Clark, 1994).

Potential policies must be based on a foundation of knowledge of the complexity and delicate balance of players in the auto and recycling industry, with perspectives on the motivations and constraints faced by stakeholders (Field III & Clark, 1994).. Since the automobile industry consumes a large fraction of materials of the total market, the auto industry must evaluate the rippling effects it has on materials suppliers (Field III & Clark, 1994).

At present, as recycling activities are based on economic opportunity, policymakers must be cautious in maintaining the balance between the economics of recycling industries and demand for recyclables. The development of effective policies will require a systemic approach that strategically considers the interactions among recycling industry stakeholders (Field III & Clark, 1994).

Stakeholders

Manufacturers can use dismantling costs to understand design tradeoffs, and to ultimately achieve designs more efficient (and more profitable) from a system-wide perspective.

Dismantlers will use the dismantling costs to understand the lowest-cost part removal choices for a targeted reduction in contaminants.

Shredders, like manufacturers, can use dismantling costs to identify economic inefficiencies that exist between them and dismantlers.

Policymakers can use the costs to help guide decisions about what regulations should be imposed on the industry.

Background Information

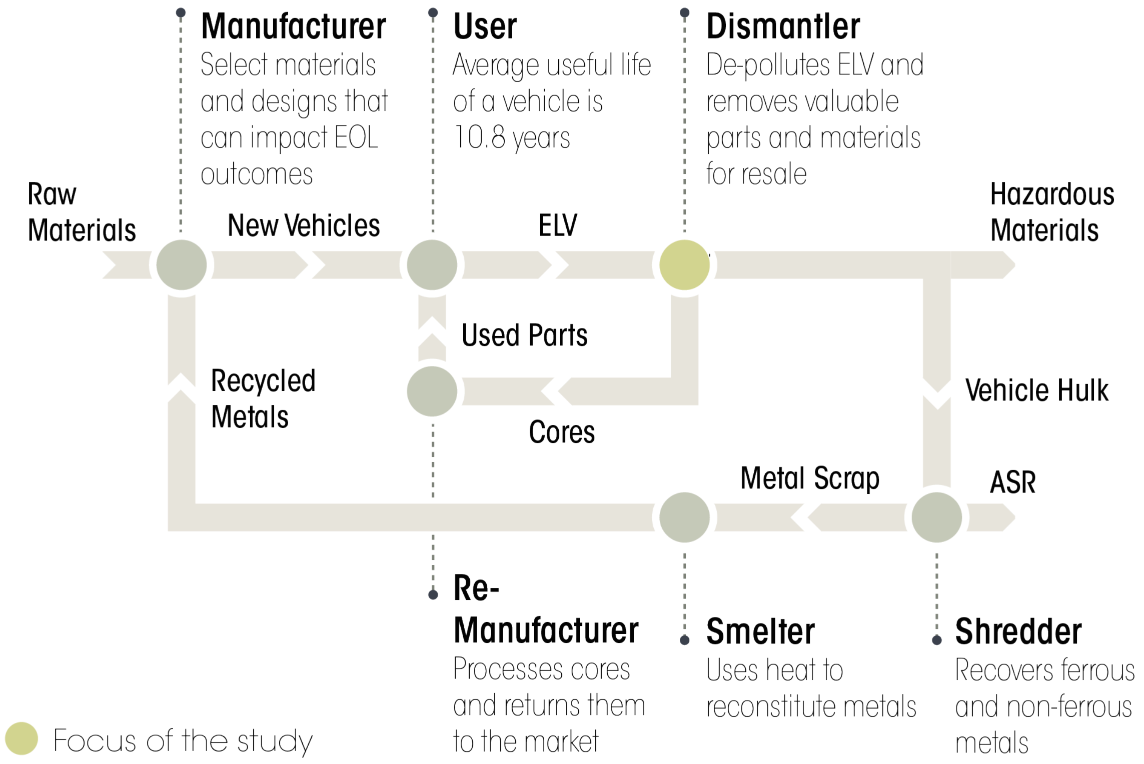
The Automobile Life Cycle

The life cycle for automobiles and auto parts is complex and well developed. Manufacturers and a vast network of suppliers produce new vehicles and sell them to the consumer. The consumer keeps the vehicle for an average of 10.8 years (Kumar & Sutherland, 2008). At the end of its lifetime, the vehicle typically goes to a dismantling facility, where it is stripped of parts and materials that have reuse or recycling value. Dismantlers sell the remaining hulk to shredding facilities, which are able to recover additional value, mostly in the form of steel. The remaining waste is called automotive shredder residue (ASR), and is typically sent to a landfill.

End of Life

The end of life stage begins when the vehicle is no longer useful to the consumer. Some vehicles are sold directly by consumers to dismantling facilities. Others are sold to dismantlers after being traded-in to dealerships or used car dealers. Yet others are totaled in accidents and surrendered to insurance companies; insurance companies then sell them to dismantlers. Regardless of the path taken,

Figure 4: The vehicle lifecycle



almost all vehicles end up at a dismantling facility. In the United States, approximately 95% of all cars go to a dismantler at the end of their useful life (USCAR, 2008).

The dismantler recovers usable parts that can be resold on the secondary auto parts market and other parts with materials of economic value. The dismantler also removes all mandatory pre-treatment parts, such as wheel weights and catalytic converters. Dismantlers are also required to remove fluids. After extracting the valuable parts, the dismantler sells the remaining vehicle hulk to a recycling facility (aka. a “Shredder”). The shredder processes the car by running it through an automobile shredder and turning it into small pieces containing ferrous metals, non-ferrous metals, and other materials. Valuable metals are recovered during the recycling process and the remaining materials are disposed of in a landfill.

Dismantlers

Dismantlers make purchasing decisions of ELVs based on the vehicle’s age and the estimated value of recoverable parts and materials. There are about 6,000 dismantlers across the United States, and about 85 percent of dismantling facilities are small, family-owned businesses (Kumar & Sutherland, 2008). Automobile end of life disassembly is carried out to recover valuable parts and/or materials, and to remove hazardous or toxic parts and/or materials (Sodhi et al., 2004). Recovered subassemblies, including the engine, transmission, radiator, catalytic convertor, fuel tanks, fluids, tires, batteries, and air bags, are removed from the vehicle. Electro-mechanical components such as engines, transmissions, starters, alternators, clutches, water pumps, and power window motors are usually remanufactured and then sold for re-use. Catalytic convertors are very valuable and sent to specialized recyclers to recover precious metals (Staudinger & Keoleian, 2001). Dismantlers are required to remove air-conditioning refrigerant gases, vehicle fluids, and batteries. Batteries are sent to a lead-acid battery recycling facilities. Air conditioning refrigerant is recovered for reuse or destroyed. Vehicle fluids, including gasoline, engine oil, ethylene glycol, transmission fluid, and windshield cleaning fluid, are all removed. Fuel tanks are recycled if they are steel; plastic tanks are sent to landfills (Staudinger & Keoleian, 2001).After removal of hazardous materials and separation of parts, the leftover hulk is crushed, sold, and transported to a shredding facility. Inspectors at shredding facilities confirm that potential sources of hazardous materials are removed. Hulks retain approximately 70 percent of the original weight of the vehicle and generally consist of structural parts, foam seats, plastic dashboards, and other materials (Staudinger & Keoleian, 2001).

Figure 5: Parts recovered by dismantler for re-manufacturing. Photograph taken at LKQ Corporation

The dismantler removes valuable parts and materials for re-sale.

Shredders

There are about 180 to 200 shredders in the US - most shredders process 400 to 500 hulks per day (Kumar & Sutherland, 2008). Shredders employ various methods to extract valuable materials from the hulk, but at the center of their operation is an automotive shredder, a device that grinds and breaks down hulks into small fragments about 10 cm long. The shredder then attempts to separate the fragments by material (Ferrão & Amaral, 2006). Ferrous pieces can be isolated with magnetic separation technologies. Non-ferrous pieces can be isolated with other post-shredder technologies, but with less efficiency (Ferrão & Amaral, 2006). Other materials are separated based on whether they can be sold in bulk or require disposal in landfills (Kibira & Jain, 2011). The waste destined for landfills is called automotive shredder residue (ASR). About 15% of the mass of a ELV vehicle becomes ASR (Kibira & Jain, 2011).

New technologies such as magnetic separators have increased the efficiency of material separation at the shredding stage. Meanwhile, high speed mechanical shredding machines have lowered costs at the shredder stage. In regards to disposal, the cost of landfill is based on the price per unit volume at the landfill, the density of the shredder residue, and the geographic region (Kumar & Sutherland, 2008).

Shredder Residue

Automotive shredder residue (ASR) is leftover scrap with limited salvageable value that is a byproduct of the automobile recycling process. It is composed of heterogeneous waste material including plastics, carpet, and glass (Tonn et al., 2003). Fluids comprise an additional 2% of ASR composition (Zorpas & Inglezakis, 2012). An ELV generates about 325 kg of solid waste, while 300 kg of this is ASR (Kumar & Sutherland, 2008).

4.3

million tons of ASR are landfilled each year, representing

3.9%

of total municipal solid waste.

Due to a high volume of automobiles entering the recycling stream, roughly 4.3 million tons of ASR are sent to the landfill each year, representing 3.9% of total municipal waste (Staudinger & Keoleian, 2001).

Contaminants

Automobiles contain several materials that pose a threat to human health or the environment if they are not disposed of properly. These contaminants include lead, mercury, cadmium, chromium, arsenic, antimony, cobalt, nickel, and zinc. For

Figure 6: Crushed hulks being delivered to a shredding facility. Photograph taken at SA Recycling facility.

Most shredders process 400 to 500 hulks per day.

Figure 7: Shredded automobile scrap. Photograph taken at SA Recycling facility.

The shredder recovers ferrous and non-ferrous metals from the hulk and disposes of the remaining materials instance, chromium is often contained in corrosion prevention coatings. Automotive fluids are also contaminants. Gasoline, oil, antifreeze, and Freon all pose dangers for the environment if not handled properly.

With 16 million new cars being produced annually, hazardous materials contained within automobiles can constitute a significant portion of the automotive shredder residue sent to landfill. These contaminants can significantly increase the cost of disposal for otherwise benign shredder residue (US EPA, 2012).

Among the contaminants contained in automobiles, mercury and lead are of particular concern. These two materials are toxic to humans, and their toxicity is magnified by their tendency to bioaccumulate in tissues. Accordingly, lead and mercury have been targeted for reduction by automobile manufacturers and legislators, both in the United States and in Europe. The Resource Conservation and Recovery Act of 1976 (RCRA) lists both lead and mercury as D-listed substances (i.e. corrosive wastes). This designation implies that both lead and mercury are considered highly toxic and are heavily regulated by the federal government.

Lead

Lead is a highly toxic metal listed by the EPA as one of the 31 priority chemicals that are targeted for reduction. The adverse effects of lead can include behavior disorders, anemia, mental retardation, and permanent nerve damage (US EPA, 1996). Lead can enter the environment through air or water. It can leach out of landfills, especially when its particle size is small (Gonzalez-Fernandez et al., 2008). Threshold amounts for lead based on federal drinking water standards are 5ppm.

Lead has been used in the following automotive parts: Starters, lead-acid batteries, wheel balancing weights, alloying agents, coatings, electronics vibration dampeners, fuel hoses, and PVC stabilizers (Gearhart et al., 2003). Most of the lead in a typical automobile is contained in the battery., Lead-acid batteries are among the most consistently recycled parts of an automobile (Battery Council, 2012); the recovery rate for lead-acid batteries is 93 percent. In the U.S., consumers are able to send used lead-acid batteries to retailers or manufacturers; auto recyclers collect batteries, recover the lead, and refine the lead for resale. The remaining, unrecovered 7% of batteries however, account for 42,000 metric tons of lead that can potentially go into the environment (*Product Stewardship*, 2003).

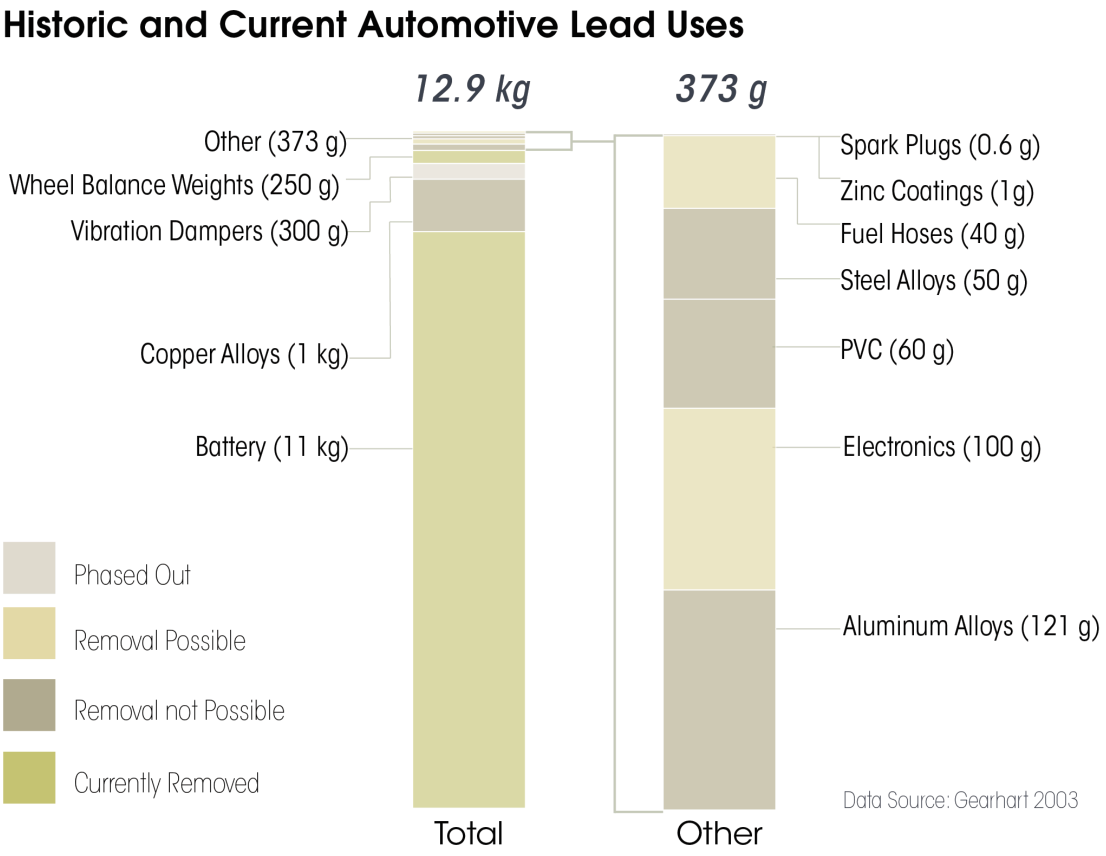
Lead has unique physical properties that can make substitution difficult. Lead has a greater density than most common metals at 11.34 g/cm3, and is softer than alternative metals with a hardness of 1.5 on the Mohr's Scale (Toxics Use Reduction Institute, 2006).

Lead from automobile batteries is the "major use of all lead in the U.S." and not just "the major use of lead in vehicles" (*Product Stewardship*, 2003). As of 2000, the automobile industry was estimated to contribute to at least 41% of known lead releases in North America (Gearhart et al., 2003)

Lead Acid Battery

About 80% of all the lead produced worldwide is used for the fabrication of automotive batteries (Kreusch et al., 2007). The EPA estimates that 99.2% of lead-acid batteries are recycled (US EPA, 2009) There are several alternatives to lead-acid batteries. For instance, nickel-hydride and lithium batteries both have higher performance than lead-acid and can feasibly be used in cars (Gearhart et al., 2003). However, these and other alternatives are more expensive than lead-

Figure 8: Automotive uses of lead



Data Source: Gearhart 2003

acid batteries, and the industry has shown little interest in using them, except in electric and hybrid vehicles (Gearhart et al., 2003).

Lead Wheel Weights

Wheel weights are used in a car to maintain balanced wheel wear and alignment. This, in turn, will extend the tire lifetime. The US EPA estimates that approximately 50 million pounds of lead is used annually to produce tire weights in autos and light trucks worldwide, with an average of 4.5 ounces of total lead attached to the four wheel rims of the automobile (US EPA, 2012). It is estimated that approximately 200 million autos and light trucks still use leaded wheel weights in the United States (US EPA, 2012). Alternative materials for wheel balance weights include steel, tin, tungsten, plastic, and zinc-aluminum-copper alloy (DTSC, 2011) (*Product Stewardship*, 2003).

Regulation has largely ended the use of lead wheel weights in new automobiles (see Section 3.5.3. Regulation in the United States). Nevertheless, the EPA estimates that 50 million pounds of lead is still used in the wheel weights of automobiles and light trucks, and should be considered an ongoing problem (US EPA, 2012). According to the EPA, there is no way to know how much lead from wheel weights is going into automotive shredder and electric arc furnace facilities (US EPA, 2009).

Vibration Dampeners

Lead was used in vibration dampeners until the late 1990s in some vehicles. Vibration dampeners connect the axle to the gearbox to reduce vibration and noise. In these older vehicles, the amount of lead in vibration dampeners typically ranges from 100-300 grams, but can be as high as 20 kilograms in sports cars (Lohse & Wirts, 2001).. Vibration dampeners have been composed of alternative materials such cast iron and polyacrylics (Lohse & Wirts, 2001).

Leaded Gasoline

While no longer a major concern, leaded gasoline deserves a mention in any discussion of lead use in automobiles. The US EPA began reduction standards for leaded gasoline in 1973, calling for a gradual reduction to a concentration of 0.10 grams/gallon by 1986 (US EPA, 1996). The US phase-out was completed in 1996 when the sale of leaded fuel for on-road vehicles was discontinued. However, the EPA allowed the continued sale of leaded gasoline for off-road vehicles, aircrafts, farm equipment, racing cars, and marine engines (US EPA, 1996).

Lead in Tin-Lead Soldering Alloys

Lead-free solder is a new development that is the result of changing welding

Figure 9: Lead wheel weights recovered by the dismantler. Photograph taken at LKQ Corporation facility.

50 million pounds of lead is still used in the wheel weights of automobiles and light trucks.

practices. A potential alternative is silver solder, but this type of solder is more expensive to produce and requires "higher soldering temperatures [that] may require different plastic materials to withstand these temperatures" (*Product Stewardship*, 2003).

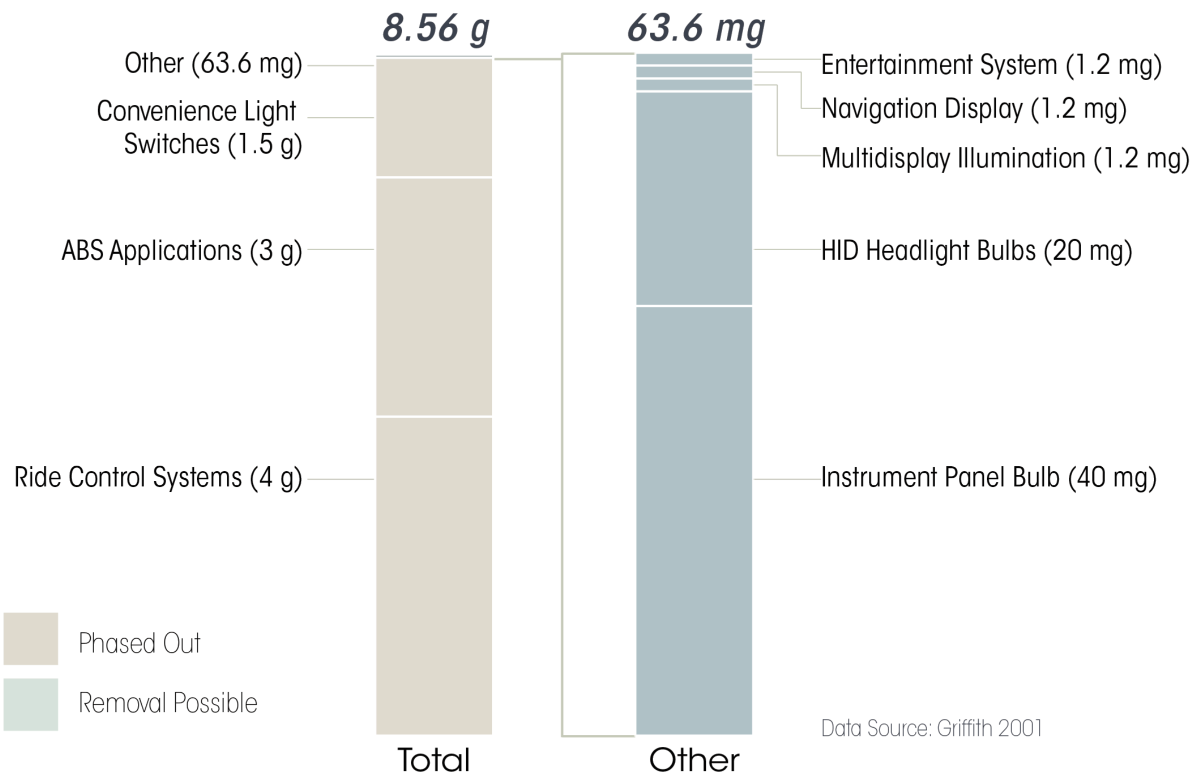
Lead Use in Other Parts

Lead may also exist in bulbs, spark plugs, paints, elastomers, hoses, plastics, electronics, and coatings (Gearhart et al., 2003) (Tomboy, 2005). It can also be incorporated into the motor (Tomboy, 2005). Some of this lead exists in paints, alloys, and coatings, and cannot feasibly be removed from the vehicle at the dismantling stage. As a result, some lead typically remains in the car when sent to the shredder, and ends up in ASR; or, if recovered by the post-shredder technology, is sent to a smelter (Gearhart et al., 2003).

Mercury

Mercury is a persistent bioaccumulative toxic metal. Mercury's acute effects include nervous system impairment via motor neuron injury and renal dysfunction. Its chronic effects include nervous system

Figure 10: Automotive uses of mercury



Data Source: Griffith 2001

dysfunction, memory deficit, decrease in motor skills, and tremors (Watts, 1997). Human exposure to mercury at concentrations of 1.0-1.5 mg/L can be fatal (Watts, 1997). Once in the environment, mercury has a tendency to form highly toxic methyl-mercury. Sulfate reducing bacteria convert mercury to methyl-mercury, which accumulates in the tissue of some fish and harms the health of people who consume them (DTSC, 2002). An environmental concentration of mercury at 0.2 ppm or higher is considered hazardous (Watts, 1997).

Automobiles may contain mercury in light switch assemblies, high intensity headlamps, display screen back lighting, and ABS brake sensors (New Hampshire Department of Environmental Services, 2010). Mercury that is not removed by the auto dismantler can become a liability for the shredder, which has the burden of properly disposing of it as an environmental contaminant.

Mercury Switches

Mercury is the only common metal that exists in liquid form at room temperature. This makes it ideal for switch and sensor applications. Prior to 2002, automobile manufacturers placed mercury switches in vehicles for convenient lighting in the hood and trunk and in anti-lock brake systems (US EPA, 2006). While they were used, mercury switches comprised about 99% of all mercury contained in a vehicle (Maine Department of Environmental Protection, 2008). Mercury switches have seen significant regulation from the Environmental Protection Agency in past years. As a result, they have been effectively phased out in all new automobiles.

Regarding the removal of mercury switches at the end-of-life, dismantlers and the auto recycling industry have been at odds over who should pay for their removal. Dismantlers state that recyclers are “best equipped to deal with” mercury switches. Recyclers contend they should not be responsible for this since they do not have “influence over the use of mercury in the vehicle” (*Product Stewardship*, 2003).

HID Headlamps

Mercury is used for both aesthetic purposes and functionality in high intensity discharge (HID) lamps (fluorescent headlamps and gas discharge bulbs). Mercury extends the lifetime of HID lamps (NEWMOA, 2008). Mercury HID headlamps are also more energy efficient than alternatives (NEWMOA, 2008). The use of mercury in HID headlamps has been increasing. Each mercury HID bulb contains approximately 5 mg of mercury (Illinois Environmental Protection Agency, 2005).

Instrument Panel Displays

Manufacturers are increasingly adding visual displays, like navigation units, computer screens, and multi-display illumination displays to automobiles. All of these contain mercury, which is used as an illuminant. Flat panel displays have about 5-10 mg of mercury. A study by the Society of Automotive Engineers revealed that "neither mercury in bulbs or instrument panel displays is routinely collected by U.S. dismantlers, except for reuse" (*Product Stewardship*, 2003). As we move into the future, consumers increasingly expect these displays as standard features, so it is likely that their use will continue to increase. Continuing research is being done on replacement technologies, as instrument panels can be illuminated with 'non-mercury lighting sources' (*Product Stewardship*, 2003). Regarding performance however, the Alliance of Automobile Manufacturers maintains that these non-mercury lighting technologies "do not meet all industry performance criteria for vehicle use" (*Product Stewardship*, 2003).

Industry Management of Contaminants

Manufacturer Initiatives

In 1993, the American Plastics Council, the Automobile Recyclers Association, and the auto manufacturer consortium USCAR (United States Council for Automotive Research) established the Vehicle Recycling Partnership to promote, research, and develop designs that improve the technical and economic feasibility of auto recycling in North America (Johnson & Wang, 1998).

To track contaminants, domestic car manufacturers have used a tracking mechanism for their parts suppliers since the 1990s. GM's worldwide specification GMW3059, which began in the late 1990s, provides an accounting system for regulated substances and process and product recycling information. Ford's version is the Restricted Substance Management Standard (RSMS). That program facilitates environmental responsibility and regulatory compliance through its processes and controls and also serves as a supplier link to the International Materials Database System (Ford, 2011). DaimlerChrysler uses its own equivalent of this system for meeting environmental, health and occupational safety requirements and product recycling reporting requirements (DaimlerChrysler, 2006).

Toyota has included the removal of contaminants as one of its stated corporate objectives (Tomboy, 2005). Toyota discontinued lead wheel weights in the late 1990s. The manufacturer also phased out lead from bulbs, spark plugs, the motor, paints, and elastomers by 2005. As of 2007, the company was still in the process of phasing out lead from initiators, valve seats, and aluminum alloys (Tomboy, 2005).

Table 1: Lead phase outs by Toyota

Part	Year
Bulbs, spark plugs, motor, elastomers & polymers	2005-2006
Valve Seat, Initiators	2006
Aluminum Alloys	2008

Design for Recycling

Among the systematic approaches to contaminant management is design for recycling. Design for recycling (DFR) is a deliberate effort to design products that can be easily reused or recycled at the end of their life. When automobile manufacturers practice Design for Recycling, there are considerations of design and of materials used, in addition to economic factors and regulatory requirements. DfR in practice improves the safety and efficiency of automotive recycling by preventing the use of hazardous materials (Saman & Blount, 2008).

Automobile designers often have to consider a variety of tradeoffs in the design and development phase of the automobile life cycle. Reusability and recyclability are low on the priority list, typically coming after safety, size, maintainability, performance, installability, manufacturability, disassembly, material cost, material availability, appearance, and customer perception (Davoodi et al., 2012). The conflict between weight/fuel economy and safety is most significant. Traditionally, the quantity of steel used in a car body is chosen to make the car stiff enough to withstand a collision. In the

Motivations for Design for Recycling

1. Direct Economic Benefits: There may be some economic advantage to the use of post-consumer materials and/or recycled materials (e.g. they may be cheaper.)
2. Reducing the Secondary Cost: By making it easier to recycle materials, manufacturers reduce the cost materials on the secondary market. If they purchase materials from the secondary market, then they benefit from the cost reduction.
3. PR: Consumers may be willing to pay a premium for recyclable designs and/or products that contain recycled materials.
4. Regulation: Government may require manufacturers to design for recycling or provide incentives for them to do so.

absence of new technology, weight reduction could come only at the cost of reduced safety. However, technology has advanced quickly, introducing new design techniques and new materials which give manufacturers the opportunity to achieve both safety improvements and weight reduction (Jambor & Matthias, 1998).

The lack of financial and policy incentives have reduced auto manufacturers willingness to design for the end of life, especially if it requires an increase in product costs (Spicer & Johnson, 2004). There is a need to create more effective life cycle management systems in order to incentivize environmentally optimal behavior at each stage of the vehicle life cycle from consumer to recycler. In order to create closed loop life cycle management, there is a need to create better information sharing systems throughout the supply chain (Srivastava, 2007).

Design for Disassembly

Disassembly is used to recover parts for re-manufacturing and reuse and is the most labor-intensive end of life management phase (Bellmann & Khare, 2000). Often, the cost of disassembly outweighs the revenue from the recovered materials, leading to more materials going to the shredder and/or landfill (Pigosso et al., 2010). Design for disassembly can benefit consumers in two ways: 1) it reduces the cost of repair since parts are easier to remove during repair (Thierry et al., 1995) and 2) it allows for easier collection of used parts that become available for consumer on the market at discounted prices. The disassembly stage can also be the lowest cost and easiest stage to remove specific parts because it "hands-on".

A minor incentive for auto manufacturers to design for disassembly is given by the insurance industry. Insurance companies consider disassembly time when they make their reimbursement schedules. A car that is easier to dismantle will have lower insurance costs than a car that is difficult to dismantle. It benefits a manufacturer to have lower insurance costs. Therefore, improving dismantling times results in a benefit to the manufacturer.

Design for Remanufacturing

Remanufacturing is believed to have a higher economic and environmental outcome than recycling (Pigosso et al., 2010). However, US auto manufacturers do not currently have incentives to design for remanufacturing. Due to stricter EU legislation, some companies such as BMW have been involved in remanufacturing and sell remanufactured parts at discounted prices to their customers (Thierry et al , 1995). In the US auto industry, manufacturers are reluctant to design for remanufacturing because this would increase the market for second hand spare parts and cut into manufacturer profits. This has caused manufacturers to create barriers for the remanufactured market, such as warranty rules (Gross, 2008). Remanufacturing can also provide a partial solution for materials for which recycling markets don’t currently exist.

Extended Producer Responsibility

Extended producer responsibility (EPR) is a regulator approach that holds manufacturers responsible for end of life costs. It was developed to promote a more integrated product management system throughout the product life cycle. By assigning the legal and economic responsibility of an end of life product to producers, it was believed that end of life considerations would be factored in during the design phase. Manufacturers would incorporate end of life costs into the price of products and work to reduce the end of life cost in order to compete on price in the market. Without EPR policies, manufacturers tend to minimize material, assembly and distribution costs, but do not give proper attention to end of life (Thierry et al , 1995).

There are several types of EPR policies commonly used (Walls, 2006):

Product take back mandate and recycling rate target

Advance recycling rate

Advanced recycling rate combined with recycling subsidy

Landfill bans

Pay as you throw

Recycling subsidies

Recycling investment tax credit

These policies were developed in the expectation that they would encourage design for remanufacturing or design for recycling. There are different optimal points in which design for recycling can reduce environmental impacts of ELVs at high cost efficiency. For example, use of a lead-free solder in the electronic control unit (*Product Stewardship*, 2003).

According to some auto manufacturers, the ELV Directive and associated effects from EPR have “already influenced further reduction in lead and hexavalent chromium” (*Product Stewardship*, 2003). In cases in which lead, mercury, cadmium, hexavalent chromium, and brominated flame retardants are still being used, alternative design techniques are being developed. In general, manufacturers are using “fewer types of materials” to lower costs, as this requires less sorting and improve vehicle recyclability (*Product Stewardship*, 2003)

Regulation of Automotive Contaminants

While the U.S. recycling infrastructure is mainly profit-driven, ELV management in Europe and Japan is driven by regulatory policies and limited landfill space. The establishment of recycling policy mandates has forced recycling infrastructures in Europe and Japan to meet their respective material recovery objectives (Kumar & Sutherland, 2008).

Regulation in the European Union

In an effort to promote sustainable automotive design practices and reduce the waste stream from ELVs, the European Union has implemented regulations that extend producer responsibility for ELVs and seek to restrict the waste stream generated by the automobile industry. A major impetus for the development of ELV directives in the EU has been the shortage of landfill capacity for waste disposal, low prices in the automotive waste scrap market, and an underdeveloped used auto parts market (Field et al., 1994).

The cornerstone of EU policy is the End-of-Life Vehicle Directive. In addition to the End-of-Life Vehicle Directive, Europe has also taken steps toward greater transparency. Major manufacturers have agreed to contribute to the International Dismantling Information Systems (IDIS) database (Leone, 2000). This database includes a common plastics coding scheme for parts over 100 grams.

Another international database that supports vehicle design transparency is the International Materials Database System (IMDS). Most manufacturers in the U.S., the EU, and Japan “require their suppliers to disclose all materials used in vehicles” through the input of materials data into IMDS (*Product Stewardship*, 2003).

Furthermore, there are several other pieces of legislation governing the management of ELVs in the EU. These include the Waste Electrical and Electronic Equipment (WEEE) Directive, which applies to electronic components in automobiles, the Directive on the Restriction of the Use of Certain Hazardous Substances (RoHS), and REACH regulations that control the disposal of select chemical substances (Konz, 2009). The EU has also implemented a Landfill Directive that restricts the composition of landfill waste (Konz, 2009).

There are varying views on how to properly incentivize design in order to avoid environmental burdens at end of life. Some criticize the current policies for failing to incentivize better product design as well as modify consumer behavior (Lane & Watson, 2012). Although the ELV policy was designed to shift the financial burden of end of life management to the manufacturers, in the EU recycling is still motivated by market forces and value of spare parts and metals and OEMs are trying to keep ELV management costs to zero. Additionally, the IDIS information exchange system designed to provide dismantling information is underused by dismantlers because limited numbers of parts can be re-sold (Gross, 2008).

ELV Directive

The End-of-Live Vehicle Directive sets recycling targets for end-of-life vehicles that mandate a 95% recycling rate by January 2015 (Konz, 2009). The ELV Directive also bans use of hazardous materials such as lead, mercury, cadmium, and hexavalent chromium. Furthermore, the Directive mandates extended producer responsibility. EPR has been successful in reducing the waste generated by the EU automobile industry by promoting design practices that increase the recyclability of vehicle components (Konz, 2009). It also increases the reuse of parts by requiring manufacturers to publish disassembly instructions (Konz, 2009). Furthermore, the End-of-Life Vehicle Directive also mandates improvements to ELV management practices such as dismantling and disposal of ASR (Giannouli et al., 2007).

Article 4(2)(a) of the 2000 ELV Directive states “Member States shall ensure that materials and components of vehicles put on the market after 1 July 2003 do not contain lead, mercury, cadmium or hexavalent chromium other than in cases listed in Annex II under the conditions specified therein.” (ELV Directive, 2000). Exemptions under the ELV Directive include lead containing alloys of steel, copper, and aluminum; lead used as a coating in fuel tanks; and mercury in headlamps (Gearhart et al., 2003). The directive also requires labeling of certain components that are exempt from the phase out including bulbs and instrument displays containing mercury, for the purpose that they should be removed from the vehicle before shredding (Gearhart et al., 2003). Additionally, the Directive has some notable exemptions including lead in lead-acid batteries, up to 2 grams of hexavalent chromium for corrosion preventing coatings; lead containing alloys of steel, aluminum and copper; lead coating inside fuel tanks, and mercury in headlamps (Gearhart et al., 2003).

RoHS Directive

The Restriction of the Use of Certain Hazardous Substances Directive 2002/95/EC was adopted by the EU in 2003 and took effect on July 1, 2006. It is closely related to the WEEE Directive of 2002, which set collection and recycling targets for e-waste. Mercury and lead are among the restricted substances under the RoHS. RoHS is often seen as complimentary to the ELV Directive because it phased out the same heavy metals, including mercury, lead, hexavalent chromium, cadmium, polybrominated biphenyls (PBB), and polybrominated diphenyl ether (PBDE). Under RoHS, the allowable concentrations of listed substances are 0.1% or 1000 ppm of homogenous material. Under the recast Directive 2011/65/EU referred to as RoHS 2, maximum concentrations have not changed (European Commission, 2011).

Regulation in Japan

The Japanese End-of-life Vehicle Recycling Law went into effect in January 2005 to cope with five million ELVs that are disposed every year. Japan's Automobile Recycling Law focuses on Automotive Shredder Residue (ASR), fluorocarbons, and airbags. For Japan's ELV law, the consumer must pay for a "recycling ticket" at the time of purchase or change of ownership (Yoshida, 2007). The Japan Automobile Recycling Promotion Center (JARC) manages the recycling funds deposited by vehicle owners until vehicles enter into ELV recycling system (Zhao & Chen, 2011). Ogushi and Kandlikar conducted a study focused on the impact of the ELV Recycling Law on recovery of automobiles from the perspective of product life cycle. They found that, in response to the ELV Recycling Law, automobile manufacturers have focused on technological innovations that enhance the levels of material recycling and part reuse. Other life cycle outcomes, such as remanufacturing of vehicles, are not likely to emerge as a result of the enforcement of the law alone (Ogushi, Kandlikar, & Dowlatabadi, 2006).

Regulation in the United States

To date, there is no federal law mandating extended producer responsibility for ELVs in the United States and no directives to reduce the waste stream from ELVs in the US. Attempts to pass national policy similar to the EU ELV Directive in the 1990s – policy that would enforce producer responsibility – failed due to strong industry opposition (Konz, 2009). As a consequence, producer responsibility projects in the US exist as voluntary "product stewardship" initiatives. However, automakers in the US are closely following the policy developments in the EU since they will need to comply with EPR policies for vehicles sold in the EU (Sutherland et al., 2004).

There are federal laws in the United States that regulate the disposal of hazardous wastes. The main federal hazardous waste policy is the Resource Conservation and Recovery Act (RCRA) of 1976, which establishes maximum allowable concentrations of RCRA-listed substances, such as lead and mercury, and creates a baseline for disposal regulations at the state level. This includes the hazardous waste leftover after the dismantling and shredding processes, which are required by federal law to have proper storage, transport, treatment, and disposal.

In the US, environmental policy on automobiles has focused on fuel efficiency, exhaust pollution, and disposal regulations rather than a system wide approach such as the ELV directive, which addresses the life-cycle of the product (EPA, 2010) (Amelia et al., 2009). Waste management, resource consumption, and toxicity issues continue, yet receive very little attention from governments, regulators, and industry (EPA, 2010). For example, the Environmental Protection Agency considers used oil as a pollutant in waterways with the potential to contaminate drinking water. It is however, not a RCRA-listed substance but it may become contaminated with RCRA-listed substances during its life cycle.

Catalytic Converters Regulations

Under federal law, catalytic converters may not be removed from a car or tampered with. Beginning in 1986, the EPA adopted the policy that stated that all cars must have catalytic converters that have been tested for certain emissions standard. Used catalytic converters are only legal if they are OE reconditioned and are installed on the same model type. The used converters must also meet a certain emission standard and be labeled specifically as used. Installers must keep records regarding installation.

The Mercury Switch Removal Program

The National Vehicle Mercury Switch Recovery Program began in 2006 as a voluntary initiative between the EPA, states, environmental organizations and industry members in order to collect the estimated 40 million mercury switches contained in scrap vehicles in the United States (US EPA, 2006). Currently, the program's funds have been depleted. However, according to NVMSRP, incentive payments will continue in states where they are required by law (AR, IL, IA, MA, ME, NJ, RI, UT, MD) or have a state funded program (IN, NC, SC, WA) but have ceased in voluntary states. All other aspects of the switch collection program are expected to continue. Dismantlers and Recyclers are strongly encouraged to continue removing switches and the program will continue to accept these switches at no cost to participants (US EPA, 2006).

Cash for Clunkers

From July to November 2009, the National Highway Traffic Safety Administration

Table 2: Timeline for mercury switch program

August 11, 2006	Memorandum of Understanding issued by EPA about the program that aimed to recover 80-90% of Mercury Switches
October 5, 2007	Significant New Use Rule; Mercury Switches in Motor Vehicles Amended 40 CFR 721. Required that mercury used in certain convenience light switches, anti-lock braking system (ABS) switches, and active ride control system switches required 90 day notice to EPA and subject to review of intent for manufacturing
February 2008	Partnership program recovers its one millionth switch
May 2010	End-of-Life Vehicle Solutions (ELVS) Program collects 3 millionth switch

(NHTSA) oversaw the Car Allowance Rebate System (CARS) program also known as "cash for clunkers". The program allowed a trade-in for vehicles 25 years old or newer with a combined 18 MPG equivalent or less.

State Regulation

Some hazardous vehicle components, such as lead wheel weights, mercury switches, and automotive fluids are regulated at the state level. In California, for example, used oil is regulated as a non-RCRA hazardous waste. Additionally, state programs like State of California Automobile Dismantlers Associations (SCADA) have been attempting to address the environmental compliance challenges faced by the dismantling industry with improved Best Management Practices. Programs like these assist the industry in establishing Best Management Practices that aim to improve dismantling practicing during the disassembly life stage of automobiles (SCADA, 2002). Unfortunately, while many responsible dismantlers attempt to comply with environmental regulations through implementation of best management practices, a substantial number of facilities operate out of compliance without storm water permits. State agencies are often have limited resources to enforce the compliance (Arbitman, 2003).

Methodology

When a vehicle reaches its end of life, dismantlers and shredders process most of the recovered materials and wastes. In the past, regulatory attempts to remove contaminants from the waste stream have done so by imposing mandates on these two industries. Under extended producer responsibility, manufacturers would bear the cost of removing these contaminants at the end of life phase. In practice, this typically means they would reimburse dismantlers and shredders for the cost of recovering and disposing of contaminants at the end of life. In order to estimate the cost of EPR policy to a manufacturer, therefore, we must estimate these end-of-life management costs.

The cost of removing contaminants from a vehicle at the dismantling stage consists primarily of two costs: disassembly cost and disposal cost. The cost of disassembly depends on labor costs and the time required for disassembly. The disposal cost depends on the cost of hazardous waste disposal and the weight of the part containing the SOC.

The following data was collected in order to determine the cost of removing lead and mercury during the dismantling stage.

- Lead and mercury content in automobile parts
- Weight of parts containing lead and mercury
- Cost of removing parts containing lead and mercury
- Cost of disposing of parts containing lead and mercury

Our study focused on the 2010 Toyota Camry. Where data for the 2010 Camry was unavailable, we used reported industry average data.

Lead and Mercury Content in Automobile Parts

The content of lead and mercury was gathered from industry reports and databases. Where data for the Toyota Camry was unavailable, industry averages were used (see Appendix E for assumptions). When a range of estimates was presented, the high estimate was generally used for our analysis (except for lead content in spark plugs).

Our analysis excluded the following materials and parts:

- Materials from which contaminants could not be removed though disassembly (PVC and alloys)
- Parts for which the contaminants have been phased out (convenience light switches, ABS, etc.)
- Parts that are currently being removed during the dismantling phase (batteries, wheel balance weights, etc.)

Table 3 and Table 4 show the lead and composition of vehicle parts and identify the parts included in our model.

Table 3: Lead content in vehicles

Part	Content Low (g)	Content High (g)	Removal Possible	Included in Model	Reason
Electronics	53	100	Yes	Yes	
Fuel Hoses		40	Yes	Yes	
Spark Plugs	0.6	0.6	Yes	Yes	
Battery		11,000	Yes	No	Currently Removed
Wheel Balance Weights	200	250	Yes	No	Currently Removed
Zinc Coatings		1	No	No	
Steel Alloys	10	50	No	No	
Copper Alloys	50	1000	No	No	
Aluminum Alloys	117	121	No	No	
PVC	50	60	No	No	
Vibration Dampener	100	300	Yes	Yes	No Longer Used
Amount Not Removed (alloys and PVC)	227	1232			

Table 4: Mercury content in vehicles

Part	Content Low (mg)	Content High (mg)	Dismantling Possible	Included in Model	Reason
HID Headlights (2)	10	20	Yes	Yes	
Multidisplay Illumination		1.2	Yes	Yes	
Instrument Panel Bulb		40	Yes	Yes	
Navigation Display (Ecology Center Estimate)		1.2	Yes	No	Same as Multidisplay Illumination in Camry
Entertainment System		1.2	Yes	No	NA
ABS Applications		3000	Yes	No	Phased out
Convenience Light Switches	700	1500	Yes	No	Phased out
Ride Control Systems	2000	4000	Yes	No	Phased out

Disassembly Costs

Labor Rates

Labor rates of $35 per hour were assumed based on reported cost of mercury switch removal (Ransom, 2001). A multiplier of 1.6 was used to account for overhead costs.

Disassembly Times

Disassembly times were estimated based on data retrieved for the Mitchell 1 auto repair information database. Data was collected for the 2010 Toyota Camry 3.5L Eng. The Mitchell 1 database provides estimates for auto part removal and replacement times. In order to estimate the amount of time needed for part dismantling, we assumed that disassembly time comprises 6.67% of total repair time based on published dismantling times of 48 seconds for convenience light switches (Quicksilver Caucus, 2005) and the repair time of 0.2 hours for a Toyota Camry convenience light switch reported in the Mitchell 1 database. By using this multiplier we were able to scale the repair times retrieved from Mitchell International to approximate dismantling times for the parts included in our analysis. See Appendix E for disassembly time calculations, assumptions, and data.

Disposal Costs

Because further processing is required to safely remove mercury and lead from automotive parts, the dismantler has to safely dispose of the contaminated part, usually by contracting with a hazardous waste management company. Hazardous waste management costs were obtained from Safety Kleen and Waste Management. Table 5 shows the costs of disposing of hazardous materials. We chose to use the lowest cost of $5.31/ gallon.

Table 5: Hazardous waste disposal costs

Volume	Price	Cost per Gallon
5G	$88.00	$17.60
15G	$132.00	$8.80
30G	$204.00	$6.80
55G	$292.00	$5.31

Because disposal costs were provided in dollars per gallon we needed to convert the weight of contaminated parts to part volume. In order to do this we used the known weight (15,000 g) and volume (509.22 in^3) of the automotive battery and assumed that other parts have a similar material density as the battery.

Data Sources

Data was collected from the following industry data sources.

Table 6: Data sources

Data Requirement	Source
Part dismantling times	Mitchell 1
Mercury and lead content in automobile parts	International Dismantling Information System (IDIS) IMERC Industry Reports (Gearhart & Mcpherson, 2001), (Menke, Defense, Griffith, & Mills, 2003)
Part Weight	IDIS, Manufacturer Specifications
Disposal costs	Department of Toxic Substances Control (DTSC) Other sources
Labor rates	Industry reports (Ransom et al., 2001)

Mitchell 1 ProDemand^{TM}

Mitchell 1 manages a database used by automotive repair professionals for car repair, collision, and mechanical issues. The ProDemand^{TM} database is used by automotive technicians to access detailed repair information and generate repair cost estimates based on service times. The database contains service times for the removal and replacement of automotive components for each auto make, model and year. ProDemand^{TM} also includes service manuals with detailed part removal and replacement instructions.

International Dismantling Information System (IDIS)

The international dismantling information system was developed in the EU to help the automotive industry respond to the ELV directive. It is managed by a consortium of manufacturers from Europe, USA, Japan, Malaysia and Korea. The database contains dismantling and de-pollution information for automobiles sold in the EU. It also contains positions and weights of the ELV directive Annex II controlled parts and provides dismantling information to air the removal of parts containing controlled substances.

Interstate Mercury Education & Reduction Clearinghouse (IMERC)

IMERC was founded by the Northeast Waste Management Officials' Association (NEWMOA) in order to provide member states to inform legislation and management of mercury containing products. IMERC manages a database that contains data submitted by manufacturers, including auto industry, on mercury-containing products. Data reported by the automotive industry includes auto components that contain mercury and the amounts of mercury contained in the component.

Table 7: Data availability

	Content (Lead)	Part Weight (Lead)	Content (Mercury)	Part Weight (Mercury)
IDIS		✓		✓
IMERC			✓	
(Gearhart et al, 2001)			✓	
(Menke et al., 2003)	✓			

Data Uncertainty

The automotive industry is a large global industry. However, there is a lack of tangible data and valuable information to inform projects assessing the environmental impacts of the industry. As a result, we had to draw on sparse datasets and make a variety of assumptions in order to evaluate the cost of removing lead and mercury during the dismantling phase of ELV processing. The following data uncertainties should be noted.

Contaminant Concentrations

There is currently a lack of standardized material composition reporting in the industry. Some manufacturer-reported data exists through programs like IMERC. However, most of the estimates used in our analysis were based on older data sets that provided estimates of average industry automotive uses of lead and mercury. This data uncertainty can create errors in our calculation of the average cost of removing contaminants at the end of life by over or underestimating the contaminant content. It could also result in the inaccurate selection of parts that contain the contaminants to be included in the analysis.

Disassembly Times

We used Mitchell Automotive Database and Mitchell1 Database to estimate dismantling times based on part repair times, assuming that dismantling time accounted for 6.67% of the total repair time for a part. However, it is likely that dismantling operations are highly variable and dismantling times are not uniformly proportional to repair times for all parts. This data uncertainty could have lead to an over- or under-estimate of dismantling costs.

Disposal Costs

Our disposal cost calculations are based on the assumption that all parts have the same material density as the battery. In reality, material densities will vary by part. For example, HID headlamps will be less dense than the battery, resulting in an underestimate of their volume and disposal cost. Additionally, disposal costs were calculated using industry average cost for disposing of hazardous materials. It is likely that these costs will vary based on volume of dismantling operations and contacts between dismantlers and waste managers. This data uncertainty can create over- or under-estimates of disposal costs.

Results

Costs of Removing Lead

The output of our model represents the total cost of the EPR policy imposed on the manufacturer at the vehicle's end of life. Table 8 shows the total cost of removing each lead-containing part from the 2010 Toyota Camry as well as the costs per gram of lead removal associated with each part. We found that it would cost the manufacturer $93.77 to recover lead-contained in the parts that can be removed during the dismantling stage. The average cost per gram of lead removal varied from $0.11 for fuel hoses to $5.24 for spark plugs.

Table 8: Removal of lead from the 2010 Toyota Camry 3.5L Eng

Part	Pb Content (g)	Part Weight (g)	Removal Time (s)	Removal Cost	Disposal Cost	Total Cost	$/g
Dash Electronics (5)	18.9	2167	912	$14.19	$1.69	$15.88	$0.84
Main Body Control Unit (1)	3.8	433	1080	$16.80	$0.34	$17.14	$4.54
Engine Compartment Electronics (3)	22.7	2600	576	$8.96	$2.03	$10.99	$0.48
Power Window ECUs (4)	15.1	1733	1440	$22.40	$1.35	$23.75	$1.57
Cabin & Seat Electronics (2)	7.6	867	576	$8.96	$0.68	$9.64	$1.28
Fuse Box	7.0	800	144	$2.24	$0.62	$2.86	$0.41
Navigation System	25.0	2870	240	$3.73	$2.24	$5.97	$0.24
Fuel Hoses	40	851	240	$3.73	$0.66	$4.40	$0.11
Spark Plugs	0.6	200	192	$2.99	$0.16	$3.14	$5.24
Total Lead Removed	140.6			**Total Cost per Car**		$93.77	
**Total Weight of Electronics 11470*							

Table 9: Removal of mercury from the 2010 Toyota Camry 3.5L Eng

Part	Hg Content (mg)	Part Weight (g)	Removal Time (s)	Removal Cost	Disposal Cost	Total Cost	$/mg
HID Headlights (2)	20	22	144	$2.24	$0.02	$2.26	$0.11
Instrument Panel Bulb	40	2	264	$4.11	$0.00	$4.11	$0.10
Multidisplay Illumination	1.2	2870	240	$3.73	$2.24	$5.97	$4.98
Total Mercury Removed (mg)		61.2		**Total Cost per Car**		$12.34	

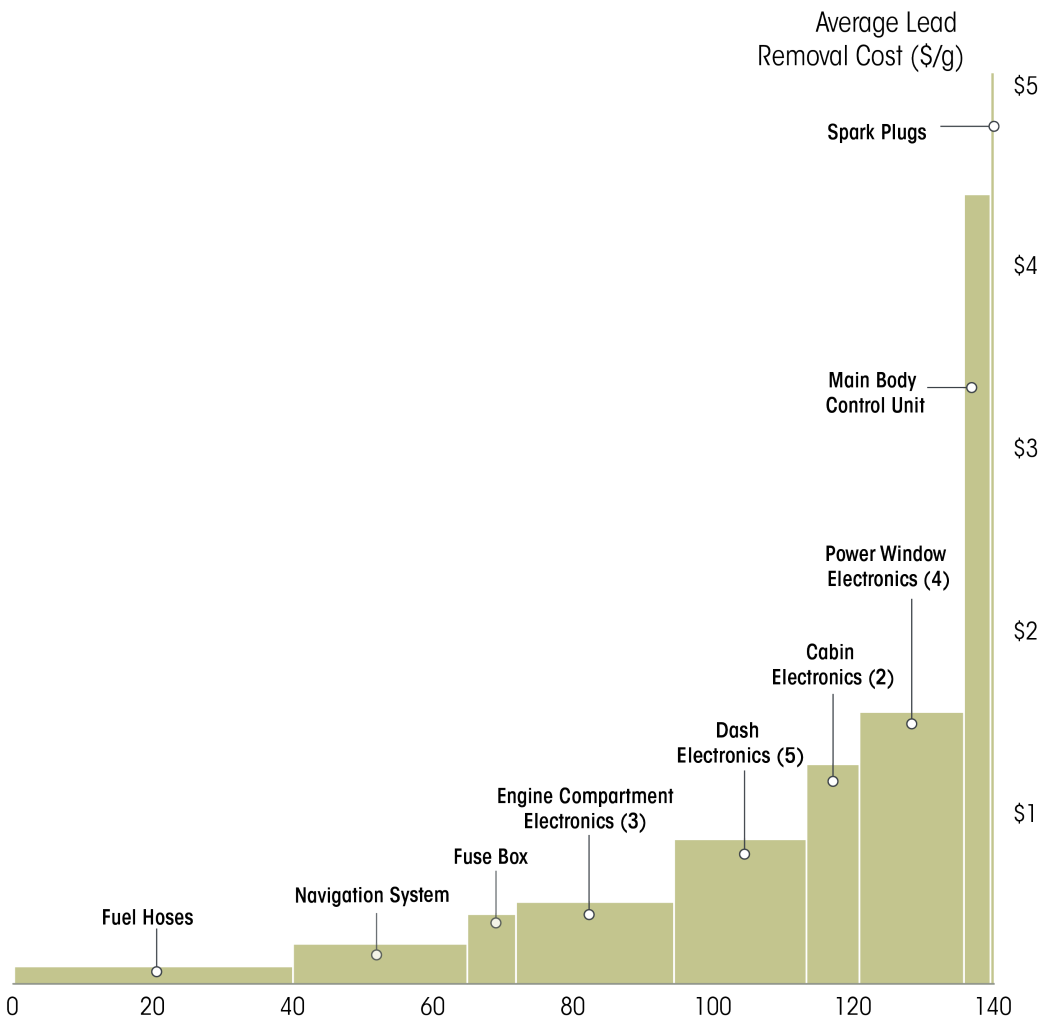
Cost of Removing Mercury

Table 9 shows the total cost of removing each mercury-containing part in the 2010 Toyota Camry and the costs per gram of mercury removal associated with each part. We found that it would cost the manufacturer $12.34 to recover mercury contained in the parts that can be removed during the dismantling stage. The average cost per gram removed varied from $0.10 for instrument panel bulbs to $4.49 for multidisplay illumination.

Cost Curves for Contaminant Removal

By arranging the SOC-containing parts in order of increasing average cost of contaminant removal, we are able to visualize the total cost of removing contaminants represented by the area under the cost curve. This visualization also allows us to identify the most cost-effective sequence of part removal. Figure 7 shows the distribution of lead in automotive parts and the average cost per gram associated with removing each part during the dismantling stage.

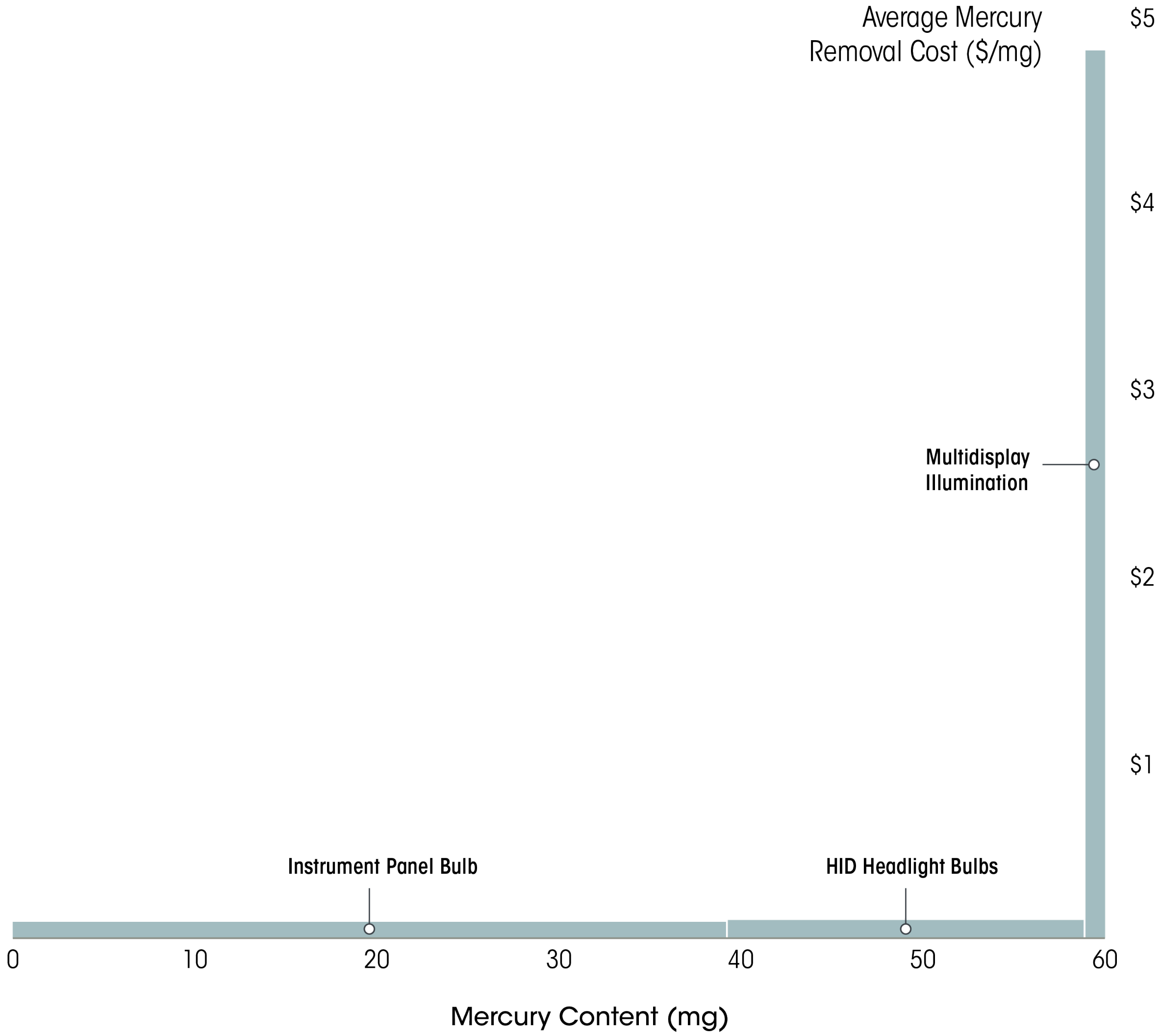
Figure 11: Cost of removing lead



We can see that dismantlers can achieve the most cost-efficient lead removal by removing fuel hoses at an average cost of $0.11 per gram of lead, thereby removing 40 grams of lead. The least cost-effective parts for dismantling are spark plugs, containing 0.6 grams of lead with a removal cost of $5.24 per gram.

Figure 8 shows the distribution of mercury in automotive parts and the average cost per gram of mercury associated with removing each part during the dismantling stage. We can see that dismantlers can achieve the most cost-efficient mercury removal by removing the instrument panel bulb at and average cost of $0.10 per gram of mercury, thereby removing 40 mg of mercury. The least cost effective part for dismantling is the multidisplay illumination, containing 1.2 grams of mercury with a removal cost of $4.98 per gram.

Figure 12: Cost of removing mercury



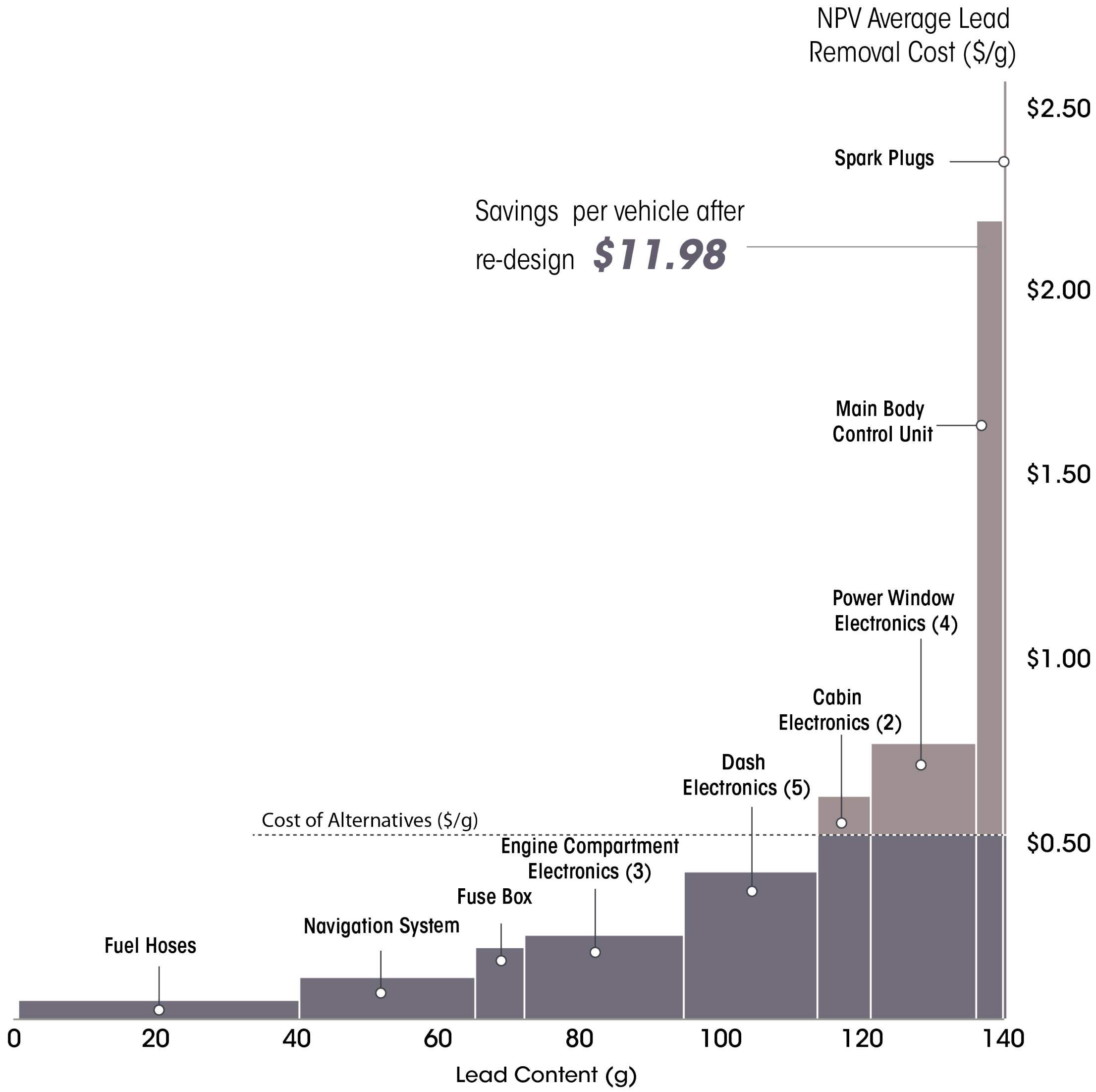
Discussion

Implications for Manufacturers

An auto manufacturer facing extended producer responsibility needs a way to compare design costs with end of life costs for removing regulated contaminants. The manufacturer can choose to remove contaminants during the design phase if the cost of doing so is lower than the EPR cost incurred by the manufacturer at the vehicle end of life. The cost curves developed in this study can guide a manufacturer's decision to remove contaminants during the design phase. By expressing the cost of eliminating contaminants during the manufacturing stage in terms of a cost per gram, the manufacturer can refer to the cost curve to determine which parts the contaminant should be removed from during the design phase.

Figure 9 demonstrates the cost-minimizing decision to remove lead during the design phase, assuming that the cost of using lead alternatives is $0.50 per gram.

Figure 13: Manufacturering decision to remove lead



Since, under EPR, the manufacturer will bear the disposal cost for lead-containing parts at the vehicle end of life (average 11 years), they would compare the net present value (NPV) of removing lead at the end of life to the cost of removing lead during the design phase. By using a discount rate of 7%, we can illustrate that the NPV of removing spark plugs, the main body control unit, power window electronics, and cabin electronics exceeds the cost of using lead in those parts during the design phase. Therefore, the most cost effective decision for the manufacturer is to remove lead from these parts during the design phase.

> *“By using a lifecycle management approach, the manufacturer is able to significantly reduce the cost of complying with EPR policy.”*

By using this lifecycle management approach, the manufacturer is able to significantly reduce the cost of complying with EPR policy. To illustrate this fact we can look at the costs of removing lead from the 2010 Toyota Camry. The NPV of the EPR cost of removing lead is $44.55 per vehicle. By using the reported sales of the Toyota Camry in 2010 (327,804) the total EPR cost for the model year (MY) amounts $31 million when the MY reaches its end of life. The NPV of these costs is $14.6 million ($44.55 per vehicle). By making the optimal design decision in the above illustrated scenario, the manufacturer is able to reduce the cost of removing lead from the waste stream by $11.98 per vehicle. This adds up to savings of $3.9 million for the MY at a total cost of $4.4 million to eliminate contaminants during the design phase. The resulting total cost of the EPR policy after the redesign is $10.7 million including the cost of using lead alternatives.

$3.9M

MY savings from vehicle redesign given a $0.50 cost of lead alternatives under EPR.

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This analysis can be repeated over a range of alternative cost values. Table 10 shows the optimal manufacturing decision to remove lead during the design phase of a vehicle given the cost of alternatives of $0.01/g $0.10/g, $0.3/g, $0.50/g, $1.00/g and $3.00/g.

Table 10: Cost-minimizing decision to use lead alternatives

Part/Cost of Alternatives	$0.01	$0.10	$0.30	$0.50	$1.00	$3.00
Fuel Hoses	✓	✗	✗	✗	✗	✗
Navigation System	✓	✓	✗	✗	✗	✗
Fuse Box	✓	✓	✗	✗	✗	✗
Engine Compartment Electronics (3)	✓	✓	✗	✗	✗	✗
Dash Electronics (5)	✓	✓	✓	✗	✗	✗
Cabin & Seat Electronics (2)	✓	✓	✓	✓	✗	✗
Power Window ECUs (4)	✓	✓	✓	✓	✗	✗
Main Body Control Unit (1)	✓	✓	✓	✓	✓	✗
Spark Plugs	✓	✓	✓	✓	✓	✗

Table 11 shows the costs and savings incurred by the manufacturer given the optimal design decision under EPR.

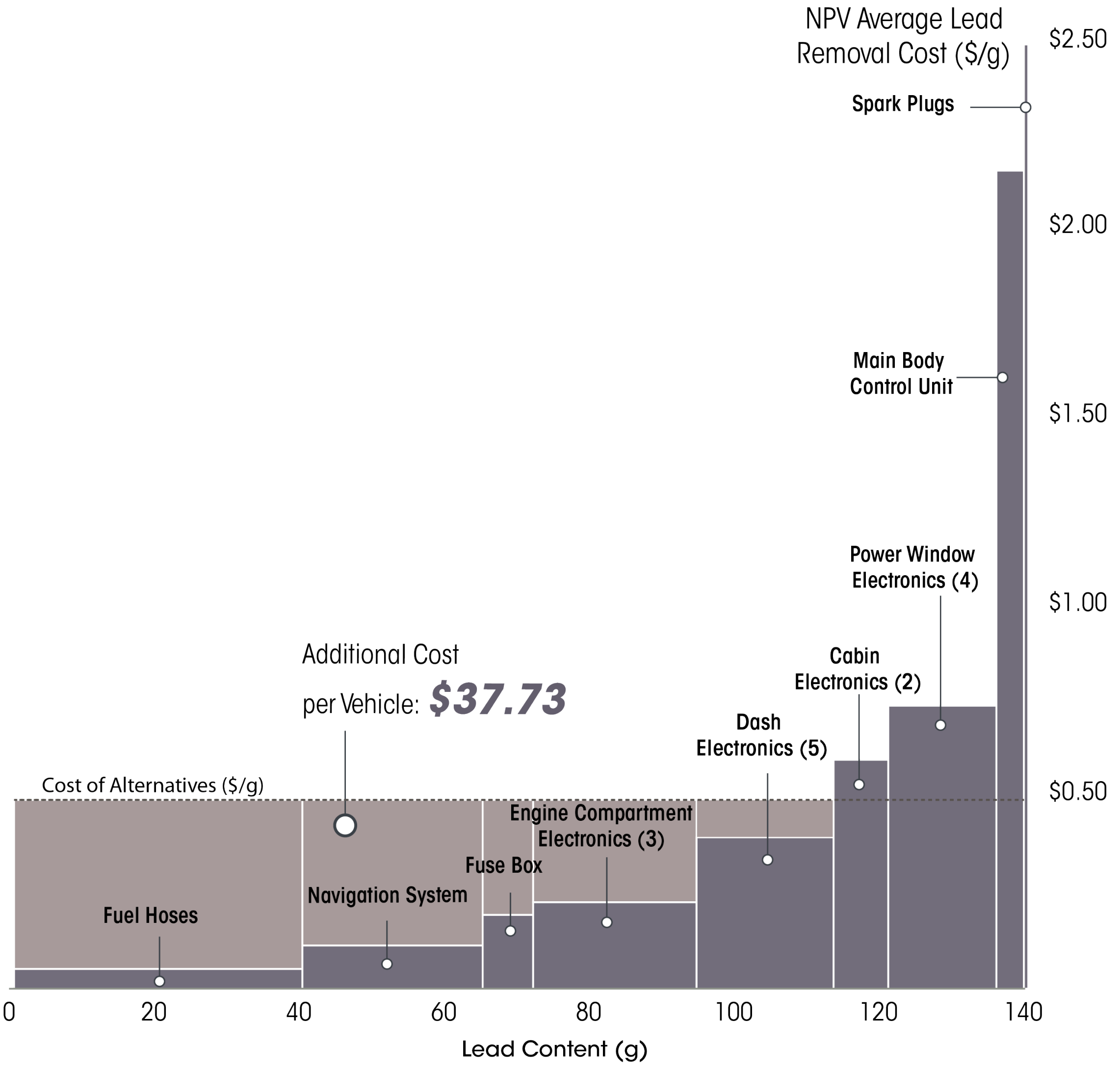
Table 11: Per vihicle and MY financial implications of cost-minimizing design decision

Cost of Alternatives ($/g)	$0.01	$0.10	$0.30	$0.50	$1.00	$3.00
Total per Vehicle cost of EPR (with redesign)	$1.41	$12.15	$25.29	$32.57	$39.29	$44.55
Total per Vehicle cost of EPR (with redesign) (in millions)	$0.46	$3,98	$8,29	$10,68	$12,89	$14,60
Redesign Cost per Vehicle	$1.41	$10.06	$13.78	$13.52	$4.38	$0.00
Redesign Cost for MY (in millions)	$0.460	$3,30	$4,52	$4,43	$1,44	$0.00
OEL Cost per Vehicle	$0.00	$2.09	$11.51	$19.05	$34.91	$44.55
OEL Cost for MY (in millions)	$0.00	$0.68	$3,77	$6,25	$11,44	$14,60
Savings from Redesign per Vehicle	$43.14	$32.40	$19.26	$11.98	$5.26	$0.00
Savings from Redesign for MY (in millions)	$14,14	$10,62	$6,3	$3,92	$1,72	$0.00

Implications for Policy Makers

In order to reduce the environmental impacts of the automobile industry, policy makers have already taken steps to prevent or manage automotive lead and mercury uses. Our model can serve as a framework for policy makers to determine the most cost-effective policies for achieving lead and mercury reduction goals. Requiring manufacturers to eliminate the use of lead-containing parts can lead to a suboptimal outcome if the price of alternatives exceeds the EOL removal costs. Figure 11 shows the cost imposed on the manufacturer by a ban on lead use. We can see that in scenario, the manufacturer will incur a cost of $37.73 per vehicle more than under the optimal design EPR scenario. By allowing for the optimal manufacturing decision to remove lead under EPR the policy maker could prevent a cost of $37.73 per car and $13.4 million for the model year. We see that a ban leads to an economically inefficient lifecycle management decision.

Figure 14: Result of lead ban



The following table shows that the cost of imposing a ban on lead exceeds the cost of imposing an EPR policy when costs of alternatives are as little as $0.10 per gram.

Table 12: Cost of imposing a lead ban for all parts

Cost of Alternatives ($/g)	**$0.01**	**$0.10**	**$0.30**	**$0.50**	**$1.00**	**$2.00**
Cost of Ban per Vehicle	$1.41	$14.06	$42.18	$70.30	$140.60	$281.20
Cost of Ban for MY (in millions)	$0.46	$4,61	$13,82	$23,04	$46,09	$92,18
Cost per Vehicle under EPR	$1.41	$10.06	$13.78	$13.52	$4.38	$0.00
Cost for MY under EPR (in millions)	$0.46	$3,99	$8,29	$10,68	$12,89	$14,60
Economic Loss per Vehicle	$0.00	$1.91	$16.89	$37.73	$101.31	$236.65
Economic Loss for Vehicle (in millions)	$0.00	$0.63	$5,54	$12,37	$33,21	$77,58

The majority of SOC use bans have historically targeted specific parts in automobiles, such as convenience light switches. The following table illustrates the potential loss of banning the use of lead in automotive parts given a range of design alternatives.

Table 13: Economic loss of ban vs. EPR per vehicle

Part/ Cost of Alternatives ($/g)	**$0.01**	**$0.10**	**$0.30**	**$0.50**	**$1.00**	**$3.00**
Fuel Hoses	$0.00	$1.91	$9.91	$17.91	$37.91	$117.91
Navigation System	$0.00	$0.00	$4.67	$9.67	$22.18	$72.23
Fuse Box	$0.00	$0.00	$0.73	$2.13	$5.61	$19.56
Engine Compartment Electronics (3)	$0.00	$0.00	$1.58	$6.11	$17.45	$62.78
Dash Electronics (5)	$0.00	$0.00	$0.00	$1.90	$11.35	$49.13
Cabin & Seat Electronics (2)	$0.00	$0.00	$0.00	$0.00	$2.98	$18.09
Power Window ECUs (4)	$0.00	$0.00	$0.00	$0.00	$3.83	$34.05
Main Body Control Unit (1)	$0.00	$0.00	$0.00	$0.00	$0.00	$3.19
Spark Plugs	$0.00	$0.00	$0.00	$0.00	$0.00	$0.31

This analysis demonstrates that by not having perfect information about manufacturing design costs, a policy maker can impose excessive costs on a manufacturer though a ban. Because manufacturers have better information about the costs of using alternatives in their design, the are able to make a cost effective choice between changing the design or removing SOCs at the vehicle end of life.

There are several additional factors that have not been incorporated into our analysis that policy makers might take into account when developing a policy to control SOCs in automobiles:

1. The costs of setting up and managing an EPR system
2. The upstream benefits of eliminating lead from the vehicle production process

For large-scale industries such as the automobile industry, establishing an infrastructure to support EPR could have a high upfront cost. However, due to the high transaction volume in the industry, the average cost of implementing EPR can be lower than the cost of enacting other policies such as bans.

Upstream environmental impacts of using SOCs include impacts during extraction and processing. A policy maker should determine which SOC pathways cause the greatest environmental concern. If impacts from ELV processing pose the highest environmental risk associated with the SOC, an EPR policy that targets the removal of the SOC in the ELV pre-treatment phase should be pursued.

Sensitivity Analysis

In order to address the data uncertainty in our analysis we performed a sensitivity analysis to determine how sensitive our results are to changes in the inputs. Table 14 shows the results on the sensitivity analysis. We see that the change in the total cost of lead removal is almost directly proportional to the change in disassembly or labor costs. Thus, our results are not very sensitive to changes in the disposal costs.

Table 14: Sensitivity of total cost estimates to changes in input variables

Input	Percent Change	Total Lead Removal Cost	Total Mercury Removal Cost
Disassembly/Labor Cost	10%	8.96%	8.17%
Disposal Costs	10%	1.04%	1.83%

Conclusion

We collected data and performed an analysis to determine the cost of removing lead and mercury from end of life vehicles. The cost curves presented in the study can inform cost-effective manufacturing decisions under Extended Producer Responsibility. Additionally, we found that the cost of removing SOCs from the waste stream under an SOC use ban exceeds the cost of removing SOCs under Extended Producer Responsibility.

Recommendations for Future Research

Estimate Design Costs

The central premise of our analysis is that, under extended producer responsibility, manufacturers must compare design costs with end of life management costs if they are to make efficient decisions. In our work, we have provided half of that equation – the end of life costs. Further work needs to be done to estimate design costs. Presumably, we can expect this to be done by the manufacturers themselves when the economic burden of extended producer responsibility falls upon them. However, there is also a role for academic research in this area.

In this context, design costs consist of 1) the cost to eliminate contaminants from the design and 2) the cost to improve dismantlability. In some cases, these costs can be estimated as the cost of substituting one material or design practice for another. For instance, dismantlability may be improved by substituting a weld with a snap fit. In these cases, good estimates of design costs can probably be found easily.

On the other hand, most design decisions involve tradeoffs. For instance, substituting one material for another may increase the weight of the car and reduce fuel economy. In these cases, estimates of design costs will require an accounting of opportunity costs, and will be very difficult to calculate.

We believe that design costs, if they can be found, would be very valuable to an understanding of design for recycling economics; we therefore recommend research in this area as a future undertaking.

Evaluate Emerging Shredder Technologies

As a player in the end of life stage, the shredder received little attention in our study. That is because the shredder is less effective than the dismantler at removing all materials except ferrous metals. New technologies are changing this situation.

As shredder technologies evolve, they will challenge our assumption that the dismantler is the inevitable low-cost option for end of life removal of contaminants. In theory, there could be some materials for which the shredder, and not the manufacturer or the dismantler, is the most efficient stage for removal.

Improve Part Composition Data Sources

Our analysis was hampered in many ways by inadequate data concerning the quantity and location of contaminants in the vehicle. Mercury and lead are the best-documented contaminants in the vehicle. Nevertheless, we were required to make several estimates in order to compile a full data set for those materials (See 4.5. Data Uncertainty).

Furthermore, there are many contaminants in vehicles for which the data was simply insufficient. In addition to lead and mercury, automobiles contain cadmium, chromium, arsenic, antimony, cobalt, and nickel. Nevertheless, there is very little data available for these materials, and we were unable to include them in our analysis.

Research which improves the body of knowledge surrounding the distribution of contaminants would help to make our analysis far more useful. In particular, we recommend an expansion of the International Dismantling Information System (IDIS). That database currently lists parts containing lead and mercury, but does not include information about the amount of lead and mercury contained in each part. Another promising direction would be to expand the International Materials Database System. That database does have more detailed information about parts, but is effectively inaccessible to everyone except industry insiders. Efforts to make that data more accessible would be a worthy research goal.

Improve Dismantlability Data Sources

Our approach sidestepped the question of dismantlability by looking at the labor times required to dismantle each part. In effect, those labor times abstract a number of complicated factors, such as the joining method and accessibility of a part.

The availability of detailed dismantlability information could modify our analysis to produce some valuable additional results. For instance, we could investigate the relative value of different joining methods, given their end of life implications. Also, dismantlability data could be used to estimate material recovery costs. With material recovery costs, it would be possible to model not only the disposal costs for lead and mercury, but also the net cost of recovering them and selling them on the secondary market. This would result in a more complete model of end of life costs. Therefore, we recommend research into dismantlability as a worthy research goal.

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List of Tables

List of Figures

Data and Assumptions

Model Using 2010 Toyota Camry 3.5L Eng: Hg

Part	Hg Content (mg)	Part Weight (g)	Removal Time (s)	Removal Cost	Disposal Cost	Total Cost	$/mg
HID Headlights (2)	20	22	144	$2.24	$0.02	$2.26	$0.11
Instrument Panel Bulb	40	2	264	$4.11	$0.00	$4.11	$0.10
Multidisplay Illumination	1.2	2870	240	$3.73	$2.24	$5.97	$4.98
Total Mercury Removed (mg)		61.2		Total Cost per Car		$12.34	

Model Using 2010 Toyota Camry 3.5L Eng: Pb

Part	Pb Content (g)	Part Weight (g)	Removal Time (s)	Removal Cost	Disposal Cost	Total Cost	$/g
Dash Electronics (5)	18.9	2167	912	$14.19	$1.69	$15.88	$0.84
Main Body Control Unit (1)	3.8	433	1080	$16.80	$0.34	$17.14	$4.54
Engine Compartment Electronics (3)	22.7	2600	576	$8.96	$2.03	$10.99	$0.48
Power Window ECUs (4)	15.1	1733	1440	$22.40	$1.35	$23.75	$1.57
Cabin & Seat Electronics (2)	7.6	867	576	$8.96	$0.68	$9.64	$1.28
Fuse Box	7.0	800	144	$2.24	$0.62	$2.86	$0.41
Navigation System	25.0	2870	240	$3.73	$2.24	$5.97	$0.24
Fuel Hoses	40	851	240	$3.73	$0.66	$4.40	$0.11
Spark Plugs	0.6	200	192	$2.99	$0.16	$3.14	$5.24
Total Lead Removed	140.6			Total Cost per Car		$93.77	

*Total Weight of Electronics 11470

Lead Part Information and Assumptions Used in Model

Part/Material	Notes	2010 Camry Information	Assumptions Made	Part Weight Assumptions	Lead Content Assumptions
Electronics	radios, navigation systems, engine control systems contain electronic devices that have printed circuit boards with lead soldering	"IDIS did not contain information for the 2010 Toyota Camry, data was available for the 2001-2007 Toyota Camry and 2007- Toyota Corolla. Lead containing parts flagged for removal were Camry 2 ECUs Navigation System Wheel Balance Weights Corolla 8 ECUs Fuse Box			
Fuse Box"	"We assume that lead will be contained in all Camry ECUs, multi-display assembly, although no fuse box location was provided in the Mitchell's database, we assume the Camry fusebox contains lead				
See IDIS data below"	The ECUs listed in IDIS for the Camry were in the engine compartment, we assume the average weight of these ECUs for the ECUs in the engine compartment of the 2010 Camry. The Corolla ECUs varied in weight, we assumed that the heavier were contained in the engine compartment and the lighter in the dash and passenger compartment, power window ECUs were assumed to weight 335 g	The total weight of lead in electronics was distributed between electronic parts proportionally to part weight			
Fuel Hoses	lead used as vulcanizing agent for fuel lines, fuel lines contain up to 4.7% lead by weight (Ecology Center)	The Mitchell's database provides repair estimates for flexible fuel lines	Although other fuel lines may exist in the Camry, we only used the parts listed in Mitchell's for our analysis	The Ecology Center report provided an estimate of 4-40 grams per vehicles of lead contained in fuel hoses. Using the provided concentration of 4.7% we calculated the weight of the fuel hoses to be 851 g	
Spark Plugs	glass found in spark plugs contains 50% lead (Ecology Center)	The Toyota Camry contains 4 spark plugs	the lower lead content estimate (0.6 g) was used because it applied to cars with 4 cylinders	We were unable to find the weight of the Camry spark plugs, we used the weights provided for the Corolla spark plugs on Amazon.com (SK16R11)	the lower lead content estimate (0.6 g) was used because it applied to cars with 4 cylinders
Battery	must be removed and recycled				
Wheel Balance Weights	typically removed my dismantlers due to profitability of lead recycling (LKQ tour), regulations exist to phase out lead weights (cite!)				
Zinc Coatings					
Steel Alloys	0.15%-0.35% added to some steel				
Copper Alloys	contain up to 4% lead				
Aluminum Alloys	secondary aluminum always contains lead as an impurity				
PVC	lead used as a stabilizer in PVC and other plastics, main PVC application is under-seal coatings, cables, upholstery, trim, PVC is 0.5-3% lead by weight (Ecology Center)				
Vibration Dampers	contain a lead weight, fairly easy to remove, not used in new cars in order to reduce weight (Ecology Center)				

Mercury Part Information and Assumptions Used in Model

Part	Notes	2010 Camry Information	Assumptions Made	Part Weight Assumptions	Mercury Content Assumptions
HID Headlights (2)	This is an increasing use of mercury in vehicles, manufacturers are required to report, manufacturers are working on developing alternatives (SAE papers)	The Toyota Camry did not contain HID headlamps according to IDIS, however the 2005 Lexus did contain HID headlamps.	We assume for the purpose of this analysis that the Camry contains HID headlamps since HID headlamps are an increasing application of mercury	According to IDIS the HID headlight bulbs weigh 22 g	
Multidisplay Illumination	This use of mercury is increasing, auto manufacturers are required to report the use of mercury in navigation systems and display illumination	According to IDIS, the 2001-2007 Camry multidisplay unit contains mercury. According to IMERC, the 2010 Camry contains mercury in the navigation display		We used the part weight provided for the 2006 Camry in IDIS	The Ecology Center reports an estimate of 1.2 mg for background lighting in navigation systems
Instrument Panel Light	The Ecology Center reports that mercury is used in backlit instrument panels	Mitchell's provides remove and replace times for this part	We assume this part will contain mercury based on the Ecology Center report information	We assume a part weight similar to a mercury light switch (2 g). The mercury switch weight was retrieved from IDIS for the 1993 Ford Explorer	The Ecology Center reports 40 mg of mercury used for speedometer systems
ABS Applications	Dismantlers are required to collect these, application phased out in 2003 (Cite!)				
Convenience Light Switches	Dismantlers are required to collect these, application phased out in 2003 (Cite!)				
Ride Control Systems	Dismantlers are required to collect these, application phased out in 2003 (Cite!)				

IDIS Data

Make Model Year	Substance	Part	Part Weight
Toyota Camry 2001-2006	Hg	Multidisplay Illumination	2870
Toyota Camry 2001-2006	Pb	ECU	830
Toyota Camry 2001-2006	Pb	ECU	774
Toyota Camry 2001-2006	Pb	Navigation System	2870
Toyota Camry 2001-2006	Pb	Wheel Balance Weight (4)	80
Toyota Corolla 2007+	Hg	Multidisplay Illumination	3116
Toyota Corolla 2007+	Pb	ECU	725
Toyota Corolla 2007+	Pb	ECU	840
Toyota Corolla 2007+	Pb	ECU	630
Toyota Corolla 2007+	Pb	ECU (2)	335
Toyota Corolla 2007+	Pb	ECU	405
Toyota Corolla 2007+	Pb	ECU	850
Toyota Corolla 2007+	Pb	ECU	170
Toyota Corolla 2007+	Pb	Fuse Box	800

Mitchell's Search Results

Ref	DESCRIPTION	HOURS	SECONDS	DISMANTLING (s)
	2010 Toyota Camry 3.5L Eng			
1	COURTESY LIGHT SWITCH - Remove & Replace Each Additional	0.2	720	48
2	COURTESY LIGHT SWITCH - Remove & Replace One	0.3	1080	72
3	THEFT DETERRENT CONTROL UNIT - Remove & Replace Certification ECU	0.7	2520	168
4	THEFT DETERRENT CONTROL UNIT - Remove & Replace Main Body ECU - [Includes: R&I Instrument Panel.]	4.5	16200	1080
5	AIR BAG CONTROL UNIT - Remove & Replace Center Sensor,Sensing & Diagnostic Module,ECU			288
6	"STABILIZER BAR CONTROL LINK - Remove & Replace Both"	0.6	2160	144
7	OCCUPANT POSITION DETECTION SYSTEM CONTROL UNIT - Remove & Replace All Applicable Models - [Includes: Calibration.]	1.2	4320	288
8	TIRE PRESSURE CONTROL UNIT - Remove & Replace All Applicable Models - [Includes: Programming.]	0.8	2880	192
	"DISPLAY ASSEMBLY - Remove & Replace All Applicable Models - [Serviced in Instrument Cluster.]"	1	3600	240
9	INSTRUMENT PANEL BULB - Remove & Replace One or All - [Includes: R&I Instrument Cluster.]	1.1	3960	264
10	HEADLAMP BULB - Remove & Replace All Applicable Models	0.3	1080	72
11	FLEXIBLE FUEL LINE - Remove & Replace Engine Area,Each	0.4	1440	96
12	FLEXIBLE FUEL LINE - Remove & Replace Tank Area,Each	0.6	2160	144
13	SPARK PLUGS - Remove & Replace Base,Hybrid,LE,SE,XLE,In-Line4	0.8	2880	192
14	SPARK PLUGS - Remove & Replace LE,SE,XLE,V6 - [Includes: R&I Upper Intake Manifold.]	2.9	10440	696
15	"POWER DOOR WINDOW MOTOR - Remove & Replace Front or Rear,Each"	1.5	5400	360
16	"AIR BAG SENSOR - Remove & Replace Center,Sensing & Diagnostic Module,ECU"	1.2	4320	288
17	"WIPER MOTOR - Remove & Replace All Applicable Models"	0.8	2880	192
18	"COOLING FAN CONTROL MODULE - Remove & Replace Base,LE,SE,XLE,In-Line4 PCM/ECM - [Includes: Programming.]"	0.8	2880	192
	2010 Nissan Altima 3.5L Eng SR			
19	FUSE BOX Remove & Replace Base,S,SR	0.6	2160	144

Lead

Lead	Notes About Parts	Removal Time (s)	Ref	Proxy	Ref	Removal Proxy (s)	Used in Model
Dash Electronics (5)	See ECU Calculations	912					912
Main Body Control Unit (1)	See ECU Calculations	1080					1080
Engine Compartment Electronics (3)	See ECU Calculations	576					576
Power Window ECUs (4)	See ECU Calculations	1440					1440
Cabin & Seat Electronics (2)	See ECU Calculations	576					576
Fuse Box (This is listed in IMDS for 2010 Corolla)		NA		Fuse Box in 2010 Nissan Altima 3.5L Eng SR	19	144	144
Fuel Hoses	In Camry there are 2 areas, engine area and fuel tank are, these are the totals	240	11,12				240
Spark Plugs		192	13				192
Mercury							
HID Headlights (2)		144	10				144
Instrument Panel Bulb		264					264
Multidisplay Illumination		240	9				240

ECU Calculations

Part	Location	Notes	Removal Time (s)	Ref	Proxy	Ref	Removal Proxy (s)	Used in Model
DASH (6)								
Certification ECU	Right side of dash		168	3				168
*Main Body ECU	Left side of dash	Listed separately due to high cost	1080	4				1080
Multi Media Interface ECU Assembly	Behind left center of dash		NA		Tire Pressure Warning ECU	8	192	192
Tire Pressure Warning ECU	Right side of dash.		192	8				192
Steering Lock ECU	Behind left side of dash.		NA		Tire Pressure Warning ECU	8	192	192
Transponder Key ECU	Behind center of dash.		NA		Certification ECU	3	168	168
PASSENGER COMPARTMENT (6)								
*Power Window ECU (4)	In respective door	Listed separately due to high cost	NA		Power Door Window Motor	15	1440	1440
Shift Lock Control ECU	Under center floor console.		NA		Airbag sensing & diagnostic module	16	288	288
Occupant Classification ECU	Front passenger's seat.		288	7				288
INGINE COMPARTMENT (3)								
Skid Control ECU W Actuator	Right side of engine compartment		NA		Wiper Motor	17	192	192
Transmission Control ECU	Left front of engine compartment		NA		Wiper Motor	17	192	192
Cooling Fan ECU	Front of engine compartment.		NA		Cooling Fan Control Module	18	192	192